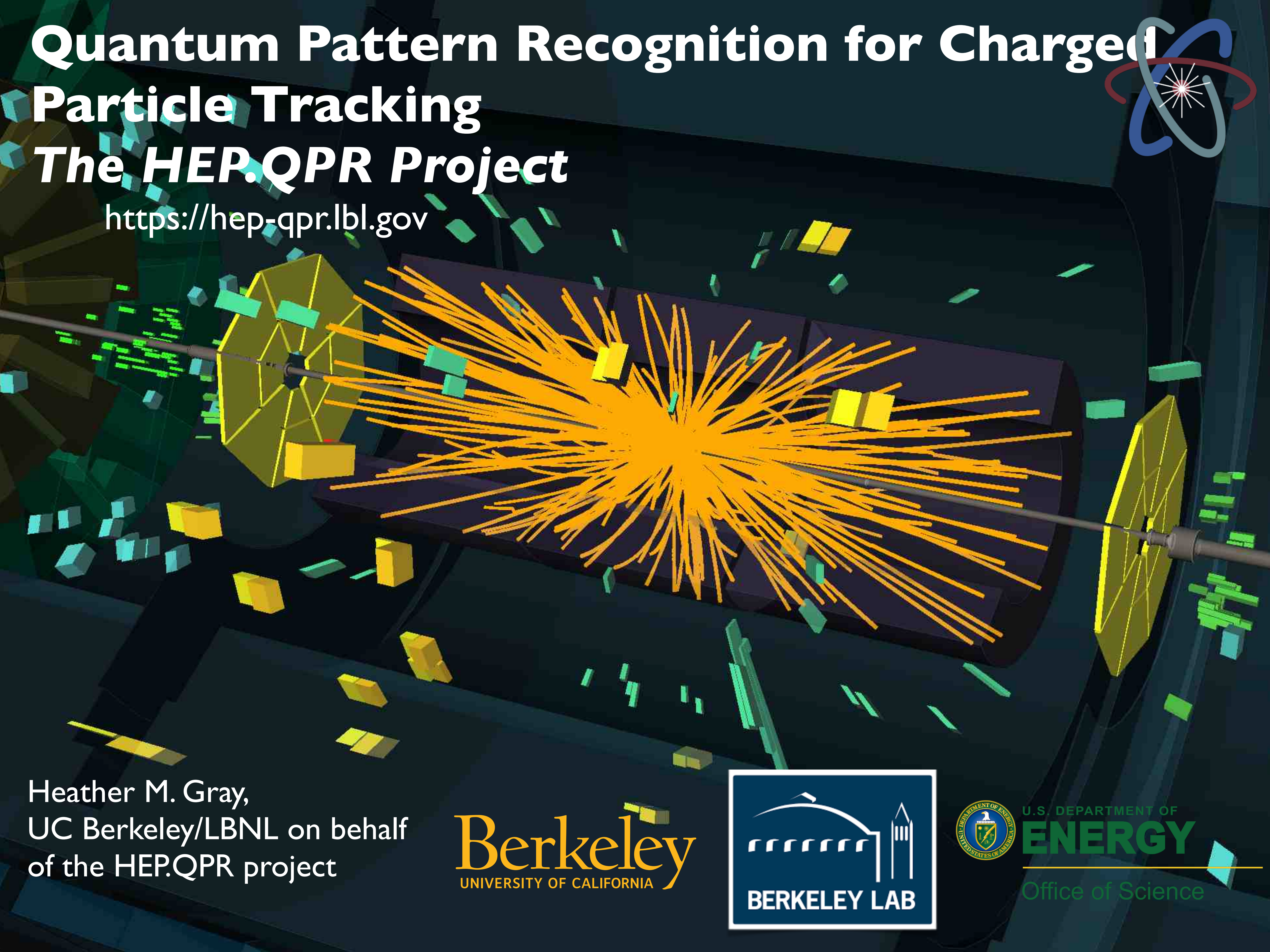
Quantum Pattern Recognition for Charged Particle Tracking

The HEP.QPR Project

https://hep-qpr.lbl.gov



Heather M. Gray,
UC Berkeley/LBNL on behalf of the HEP.QPR project

Berkeley
UNIVERSITY OF CALIFORNIA

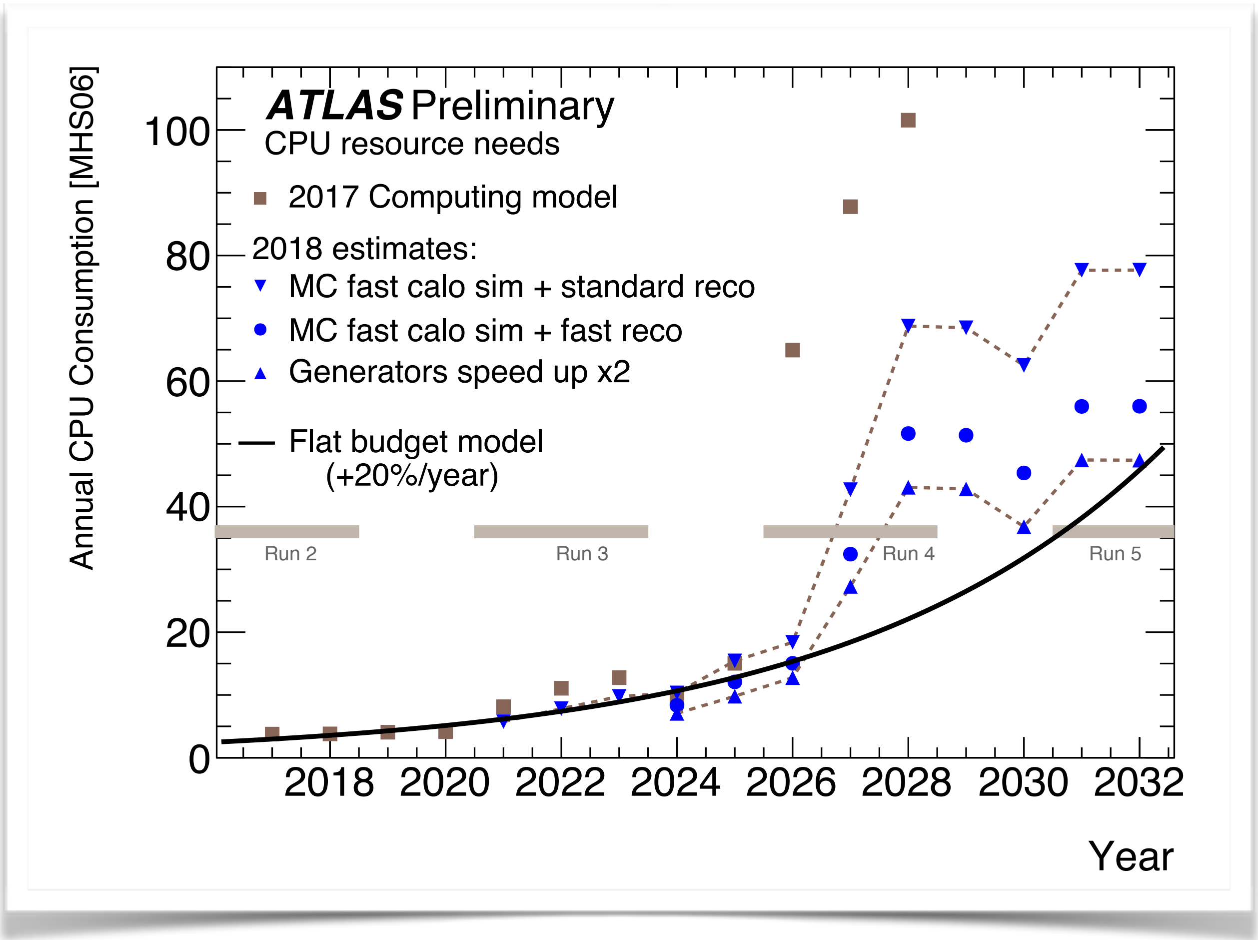
BERKELEY LAB

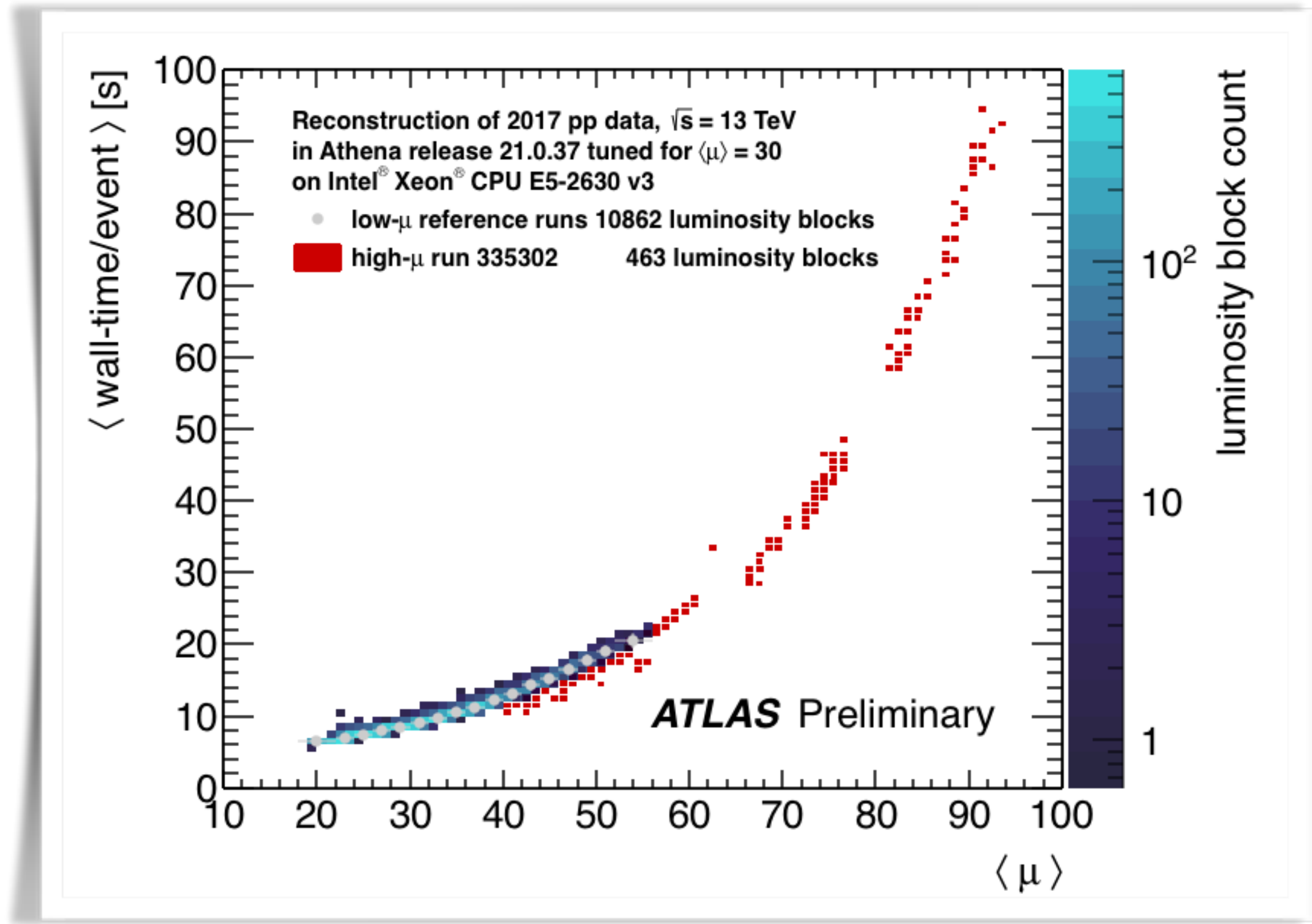
U.S. DEPARTMENT OF ENERGY
Office of Science

Computing for HL-LHC

- The HL-LHC environment is expected to pose a **challenge** for computing
  - Increased **luminosity**
  - Increased **read-out rates** (trigger+detector upgrades)
  - Increased **pile up**
- Currently project to need more CPU time than will be available
  - Dominated by **track reconstruction**
- Also expect to need 10x more disk storage

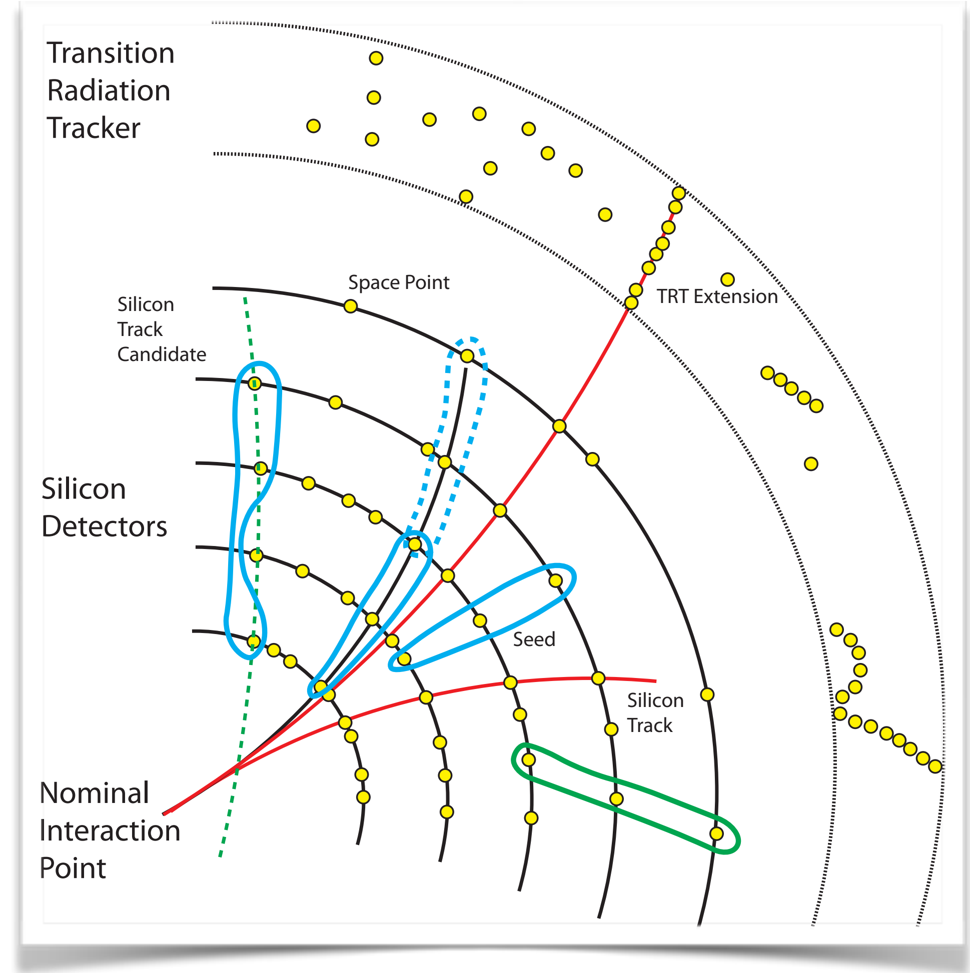
ref





Tracking Algorithms: Current Approaches

- Methods for track finding can be classified as either global or local
  - **Global**: Treat all measurements simultaneously
    - Hough, Legendre transforms
  - **Local**: Process measurements sequentially
    - track road, track following
- Tracking algorithms for silicon detectors at the LHC generally follow a multi-step local track following algorithms based on the Kalman filter
- Such local algorithms provide opportunities for parallelisation, but the execution time scales with the number of tracks

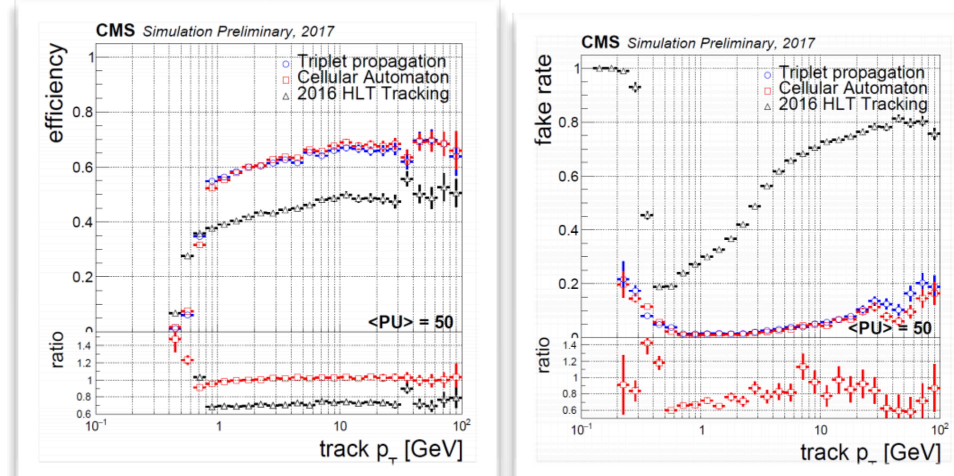


Space point formation
↓
Seed finding
↓
Track finding
↓
Ambiguity Solving
↓
TRT Extension

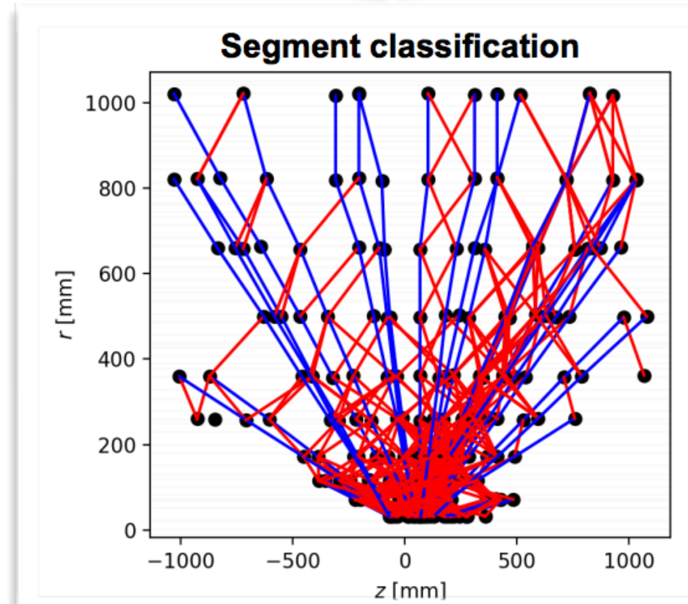
Review

Tracking approaches for HL-LHC

- Many new approaches are currently being explored for the tracking problem for the HL-LHC
- Some focus on developing new algorithms, with many of these projects focussed on machine learning
  - e.g. cellular automata, TrackML challenge, graph NNs
- Others focus on exploiting new hardware such as GPUs and FPGAs
  - Exploit parallelisation, but programming environments are challenging



F. Pantaleo

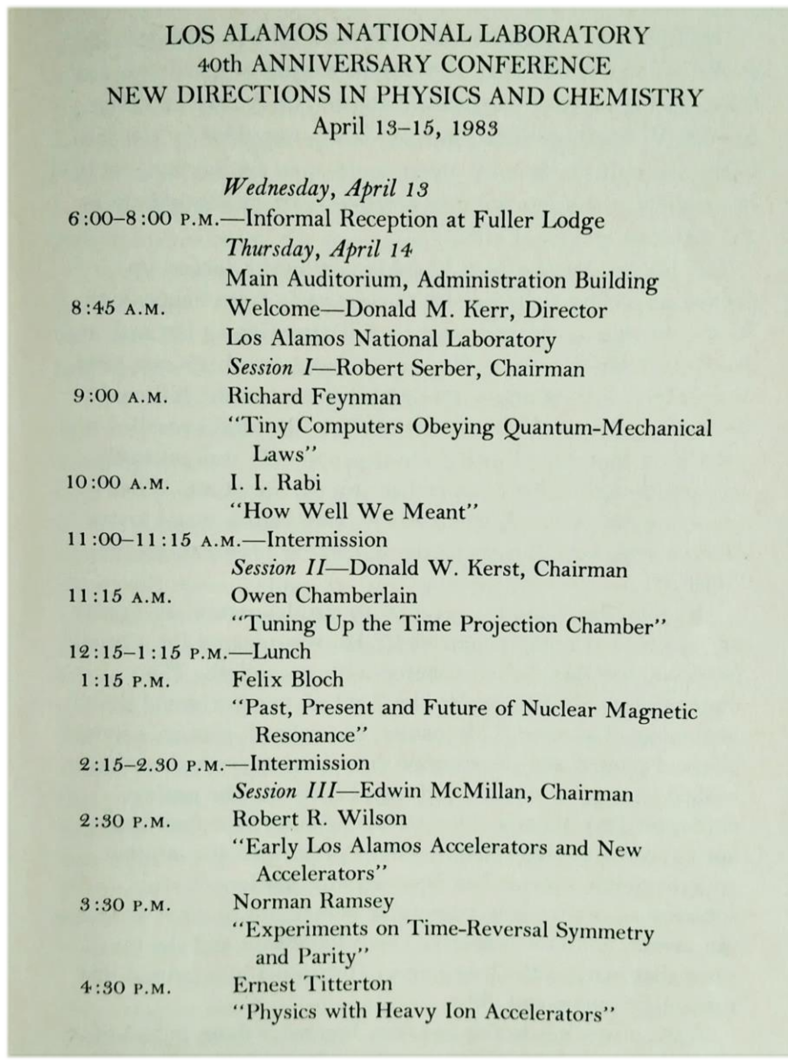


S. Farrell

See talks by J.R. Vlimant, P. Calafiura and others

Initial ideas of quantum computing

"Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws."



LOS ALAMOS NATIONAL LABORATORY
40th ANNIVERSARY CONFERENCE
NEW DIRECTIONS IN PHYSICS AND CHEMISTRY
April 13–15, 1983

Wednesday, April 13

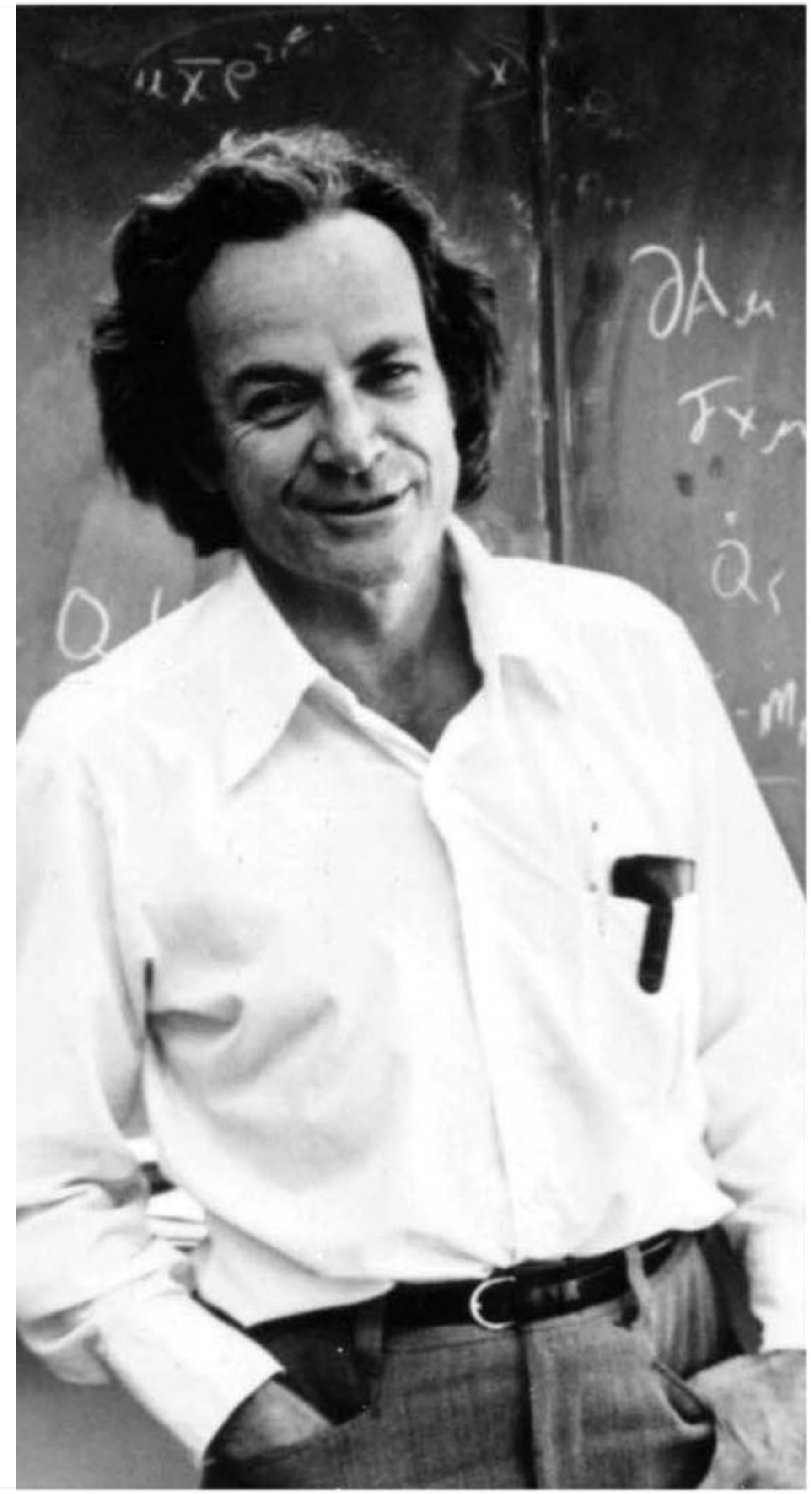
6:00–8:00 P.M.—Informal Reception at Fuller Lodge

Thursday, April 14

Main Auditorium, Administration Building

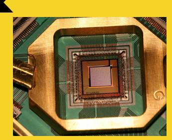
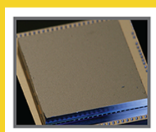
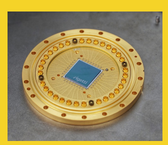
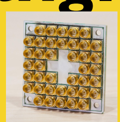
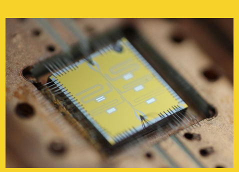
8:45 A.M.	Welcome—Donald M. Kerr, Director Los Alamos National Laboratory
	Session I—Robert Serber, Chairman
9:00 A.M.	Richard Feynman "Tiny Computers Obeying Quantum-Mechanical Laws"
10:00 A.M.	I. I. Rabi "How Well We Meant"
11:00–11:15 A.M.—Intermission	
	Session II—Donald W. Kerst, Chairman
11:15 A.M.	Owen Chamberlain "Tuning Up the Time Projection Chamber"
12:15–1:15 P.M.—Lunch	
1:15 P.M.	Felix Bloch "Past, Present and Future of Nuclear Magnetic Resonance"
2:15–2:30 P.M.—Intermission	
	Session III—Edwin McMillan, Chairman
2:30 P.M.	Robert R. Wilson "Early Los Alamos Accelerators and New Accelerators"
3:30 P.M.	Norman Ramsey "Experiments on Time-Reversal Symmetry and Parity"
4:30 P.M.	Ernest Titterton "Physics with Heavy Ion Accelerators"

RICHARD FEYNMAN (1982)



S. Montangero

Current Quantum Technologies

Quantum Chip	Qubits	Announced	Qubit Archetype	Computing Model
D-Wave XX & 2000Q  	~5000	02/2019	Superconducting **flux** qubits	Quantum annealing
	2048	01/2017		
IBM 20Q and 50Q  	20	11/2017	Superconducting **transmon** qubits	Quantum circuits
	50	11/2017 (tests)		
Rigetti 19Q 	19	12/2017	Superconducting **transmon** qubits	Quantum circuits
Intel Tangle Lake 	49	01/2018 (tests)	Superconducting qubits	Quantum circuits
Google Bristlecone 	72	03/2018 (tests)	Superconducting **transmon** qubits	Quantum circuits
UC Berkeley QNL 	4 (8)	2017	Superconducting **transmon** qubits	Quantum circuits
	64	2022 ?		

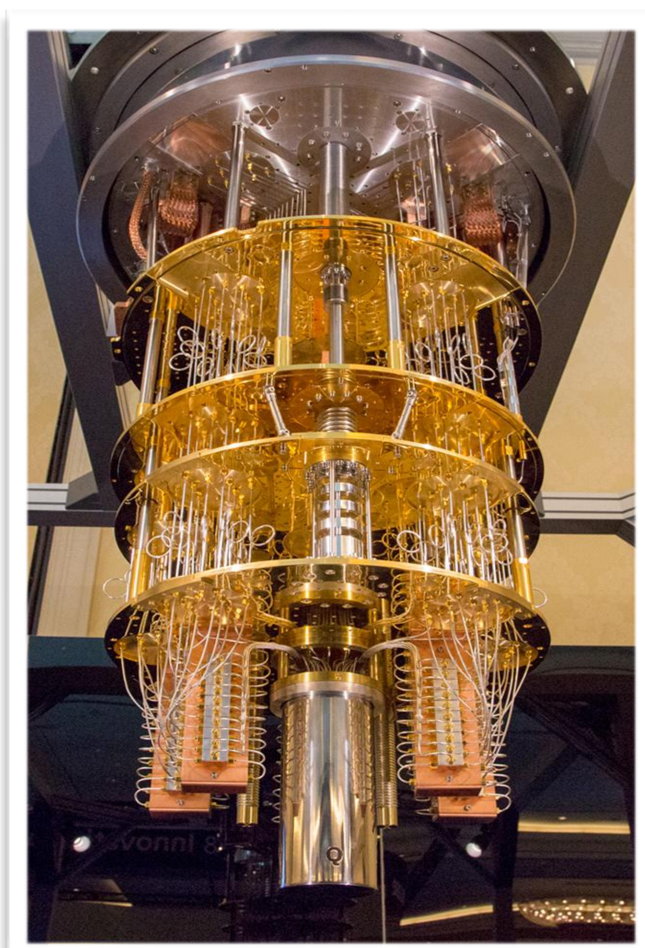
arXiv:1801.00862.pdf

Slide credit: I. Shapoval

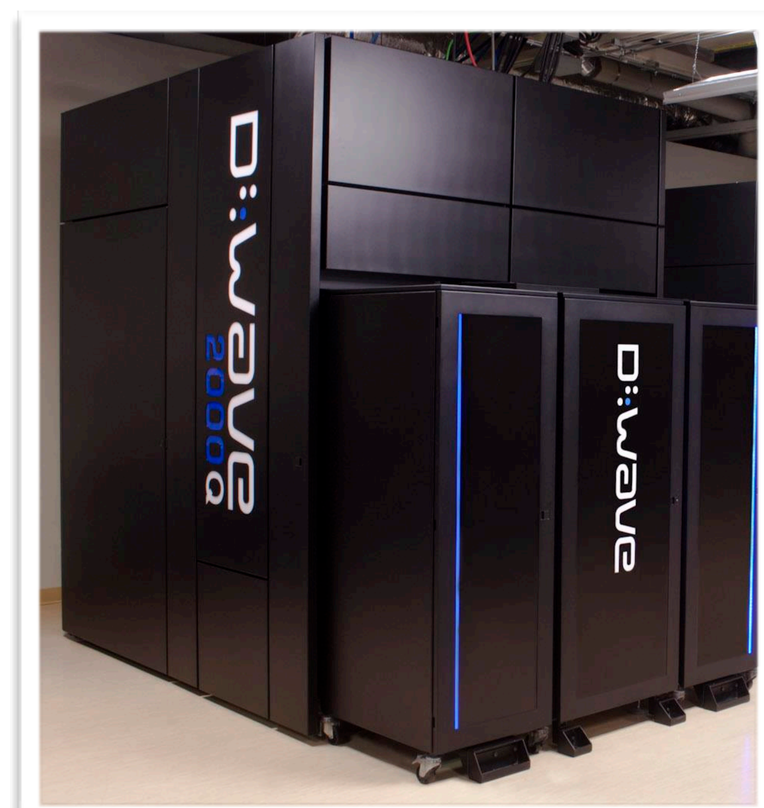
Noisy Intermediate Scale Quantum (NISQ)

- Current state of the art quantum computers fall into two main categories
  - Quantum annealers, e.g. D-Wave (2000 qubits)
  - Universal quantum computers, e.g. IBM Q (20 quits)
- All quantum computers are not equal: challenges include connectivity and noise

IBM 20Q Tokyo chip



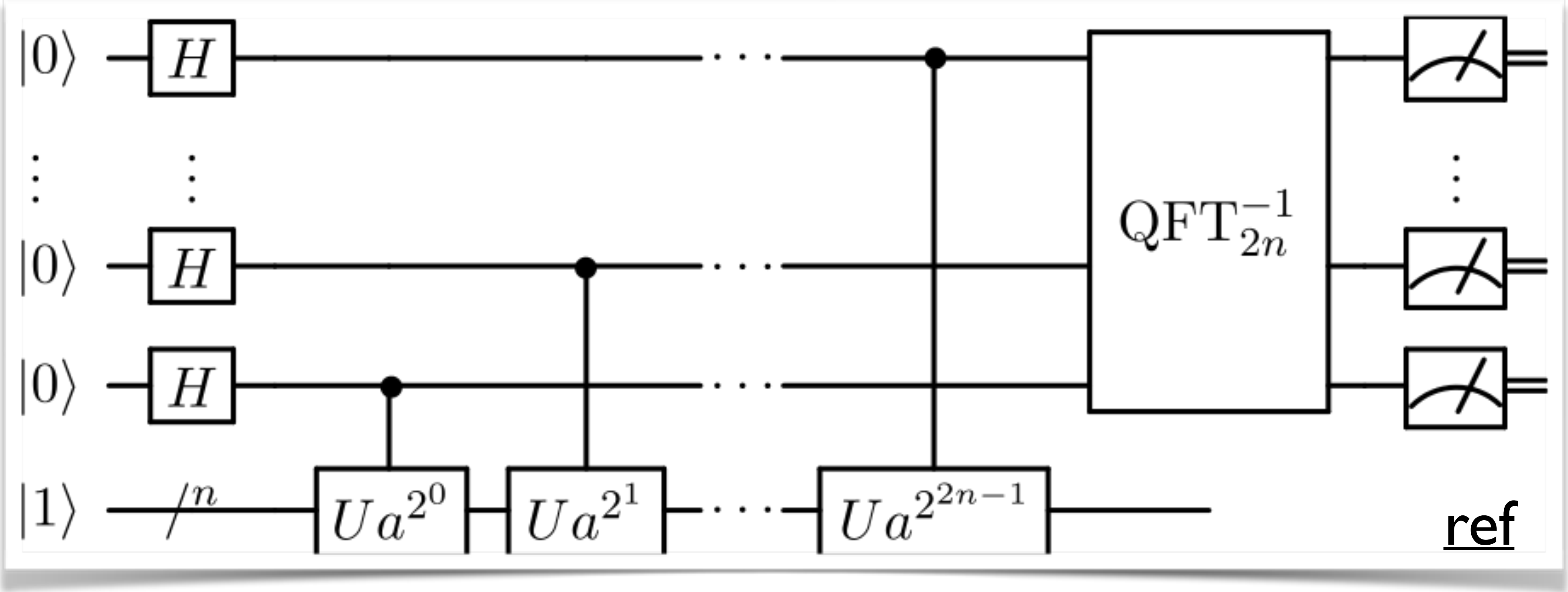
D Wave



arXiv:1801.00862.pdf

Not all qubits are equal

Quantum Circuits



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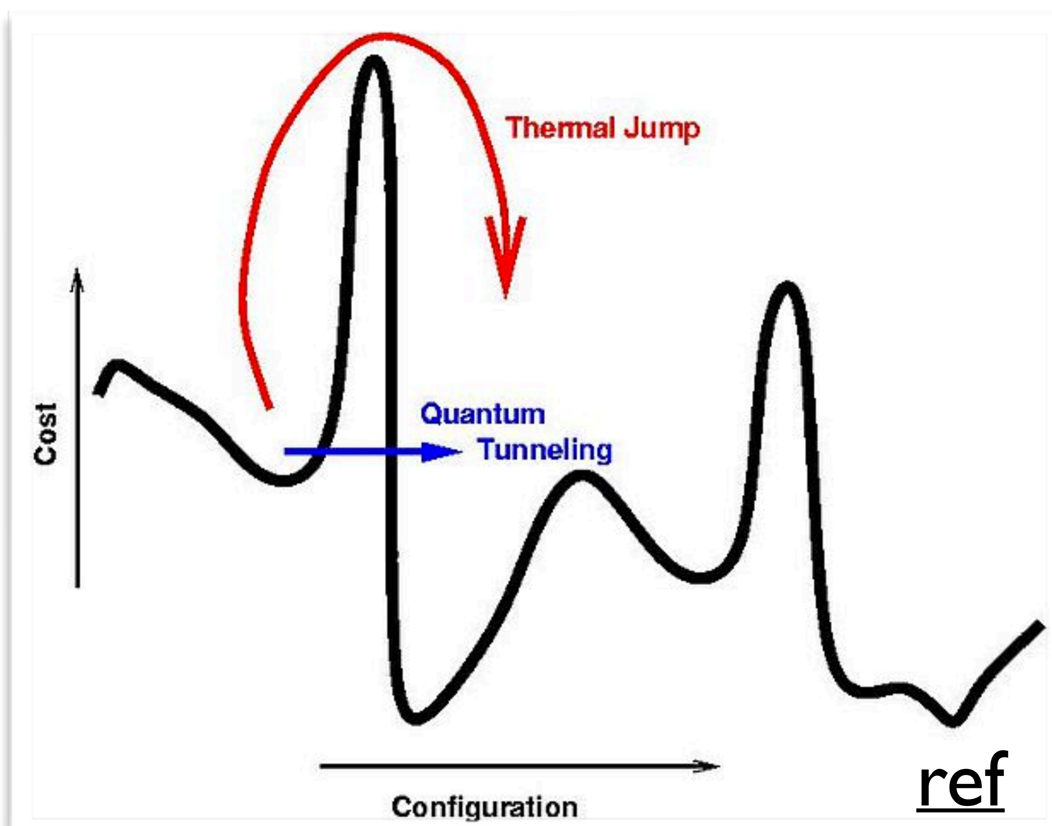
Quantum Annealing



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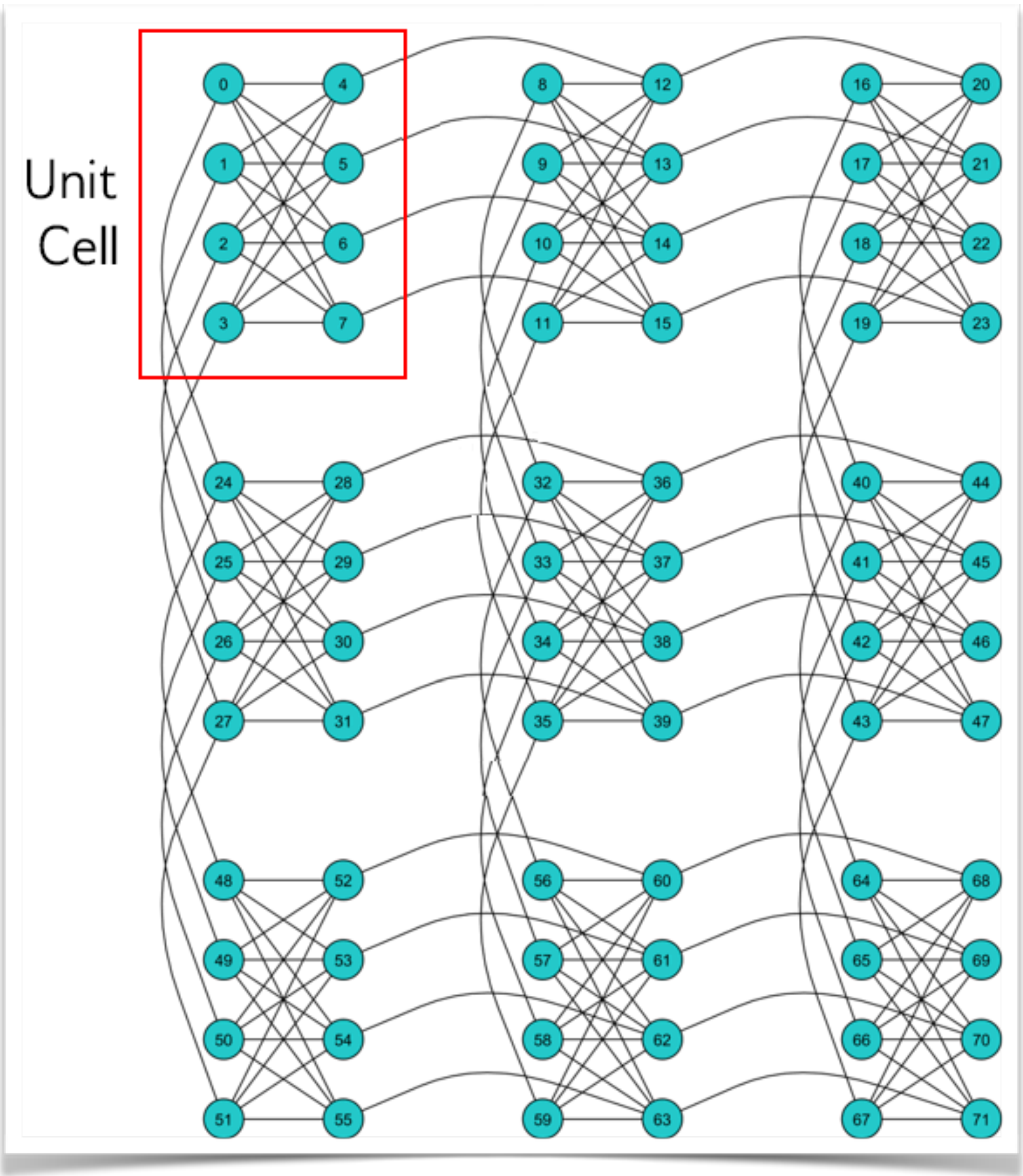
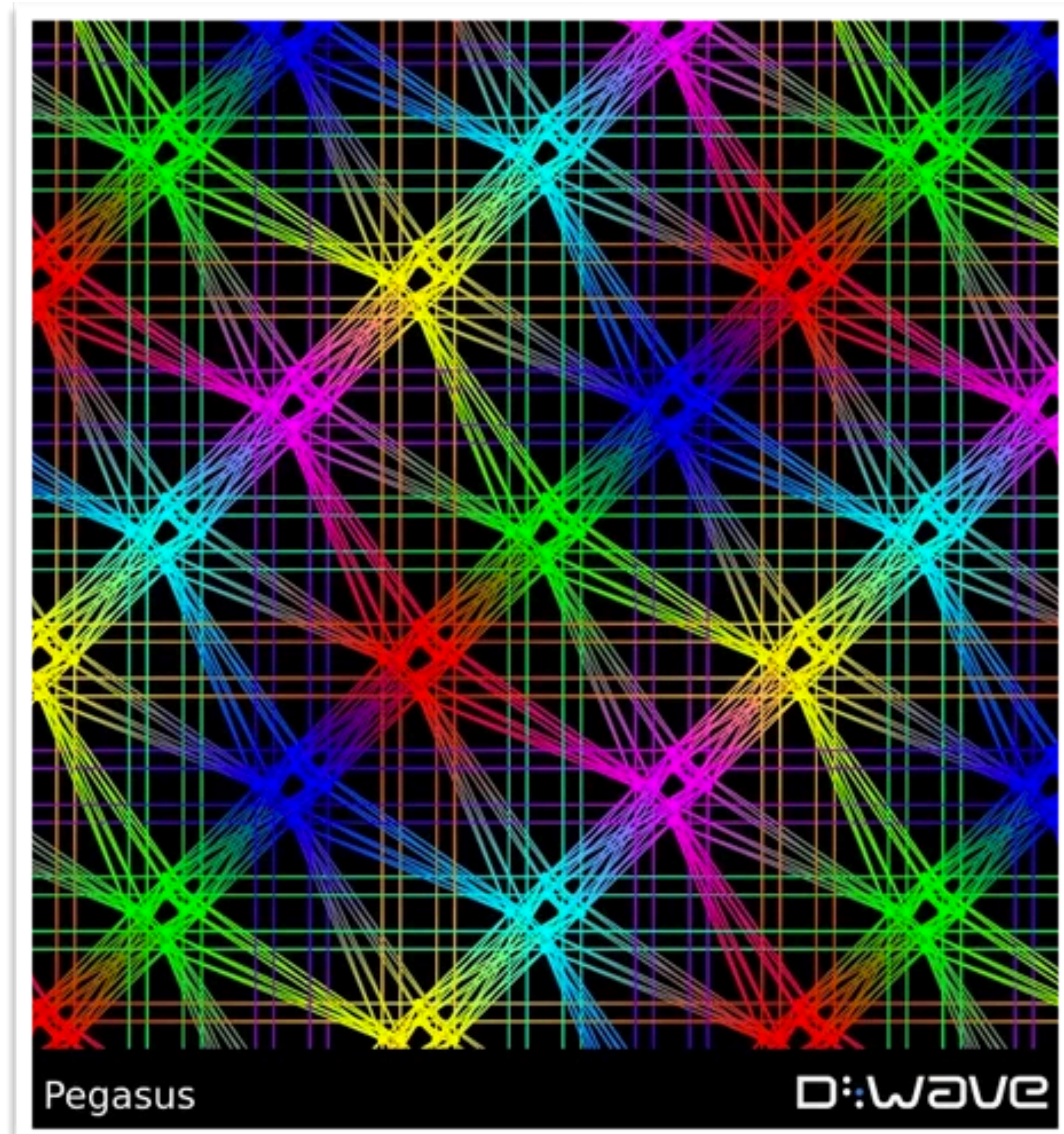
D-Wave Connectivity



D-Wave Chimera
(current)

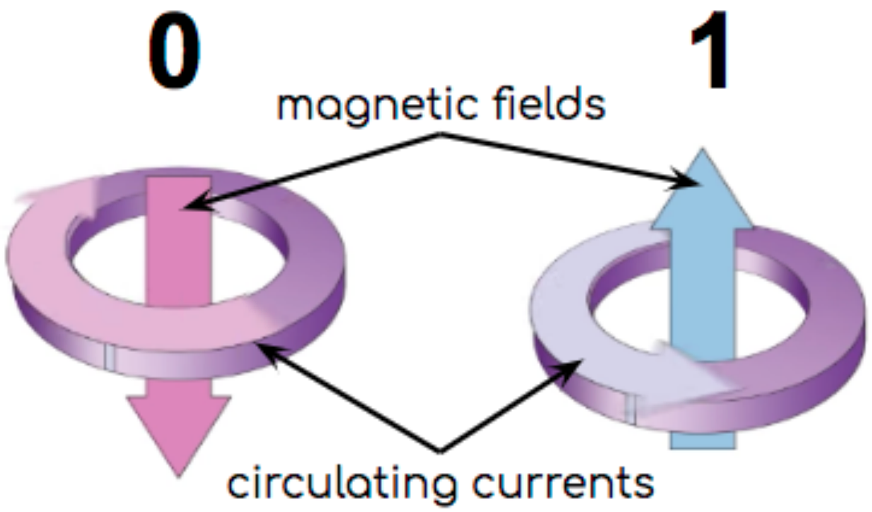


D-Wave Pegasus
(next gen.)

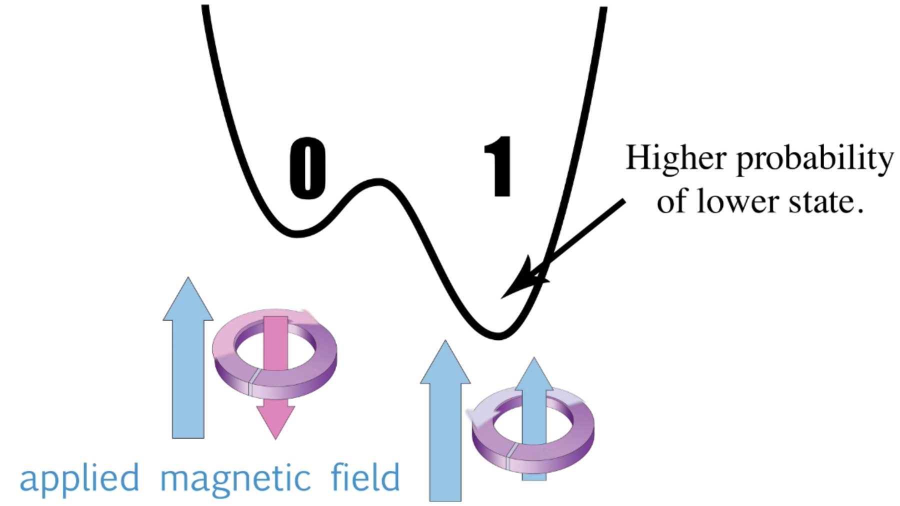
Ref: dwave

Quantum Annealing on D-Wave computers

source: dwavesys on YouTube

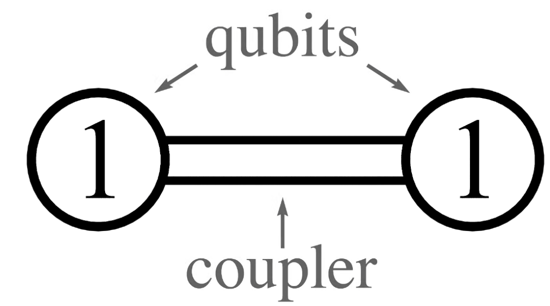


qubits ⇒ q_i



bias weights ⇒ a_i

degree to which a qubit tends to a particular state



coupling strength ⇒ b_{ij}

degree to which two qubits tend to the same state

$$O(a;b;q) = \sum_{i=1}^{N} a_i q_i + \sum_{i}^{N} \sum_{j}^{N} b_{ij} q_i q_j \quad q_i \in \{0,1\}$$

QUBO

Quadratic
Unconstrained
Binary
Optimisation

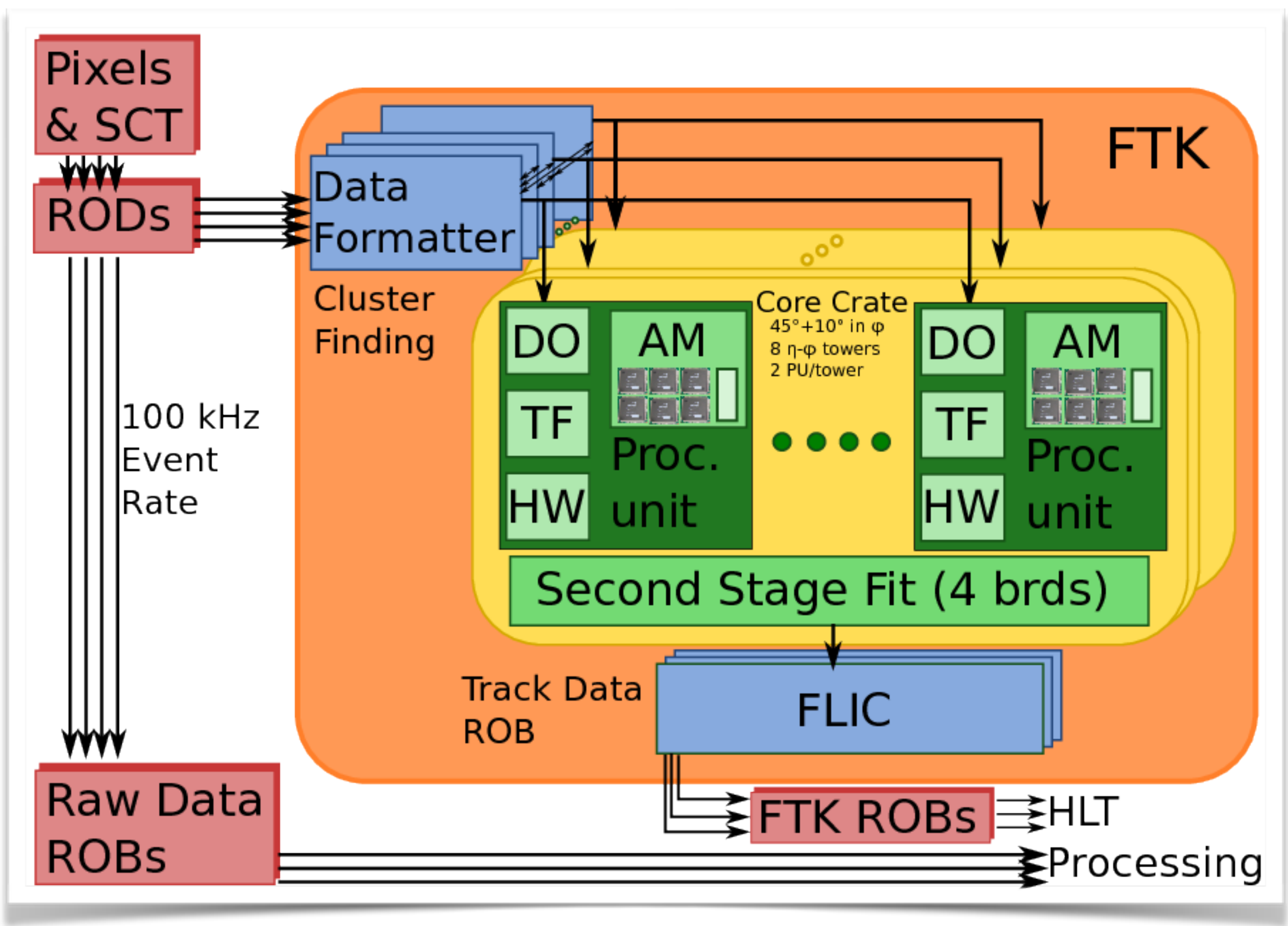
Slide credit: L. Linder

Track Reconstruction
I. Associative Memory

arXiv:1902.00498

Tracking with Associative Memory

- Store possible track patterns directly in hardware
  - Direct mapping from hit patterns to tracks
  - Avoids scaling with combinatorics
  - Can be sensitive to changes in detector conditions
- Currently being installed within ATLAS as the Fast Track Trigger (FTK)



Quantum Associative Memory

- Theoretically proven asymptotic advantages of circuit-based QC
  - Optimal* recall of unstructured memories
  - Optimal memory capacity

Strategy

- Memorize N patterns by assembling a quantum superposition of the basis states:

$$|\Xi\rangle = \sum^{N} \alpha_i |\xi^i\rangle, \qquad \alpha_i \in \mathbb{C} \;\wedge\; N \leqslant 2^n \;\wedge\; \sum^{N} |\alpha_i|^2 = 1$$

- Apply generalized Grover's algorithm to amplify the amplitude of a pattern being recalled.
- Measure memory

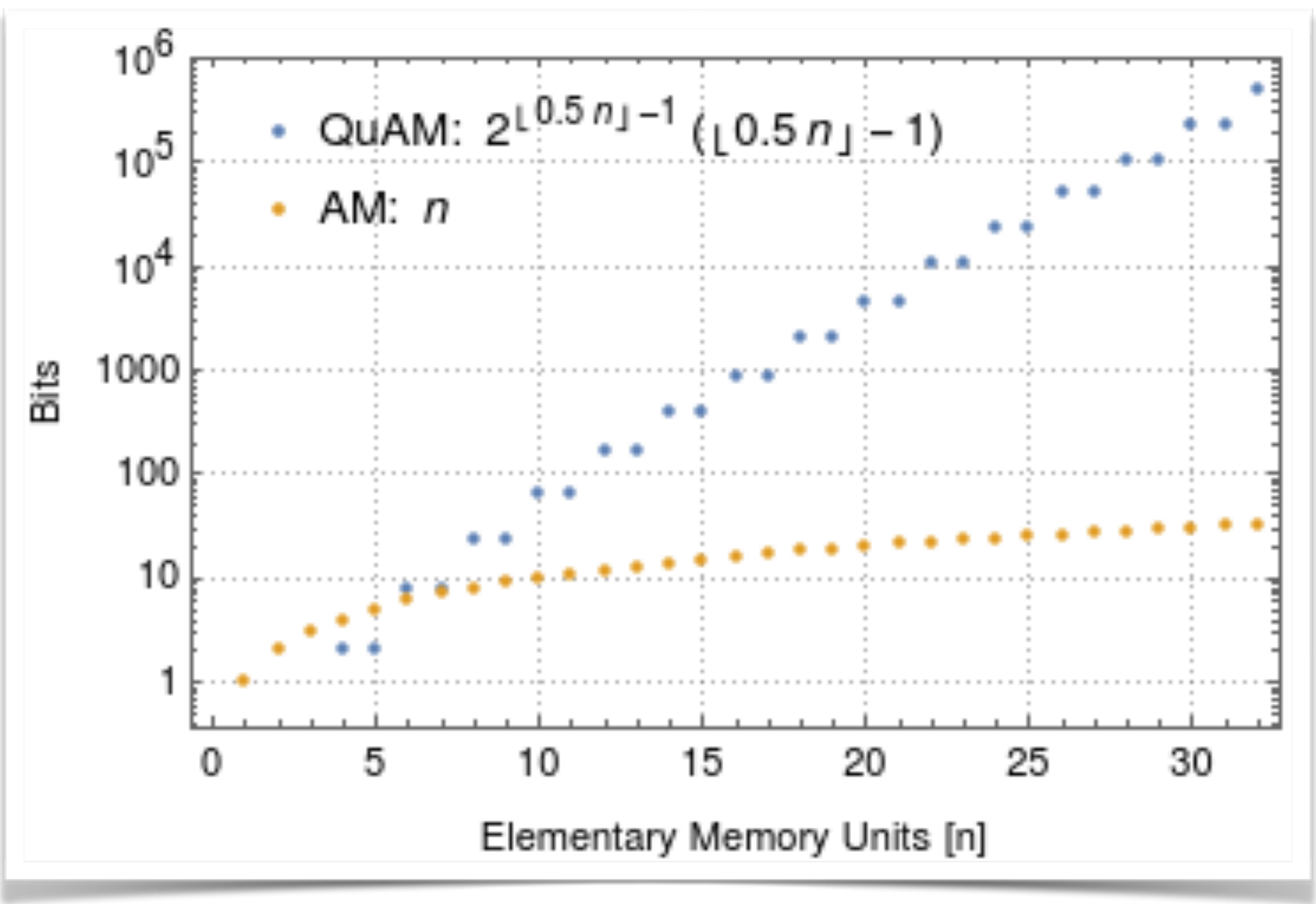
*an algorithm is optimal if no other algorithm can outperform it by more than a constant factor

Storage Capacity

Exponential storage capacity (2d)
Requires 2(d+1) qubits to operate

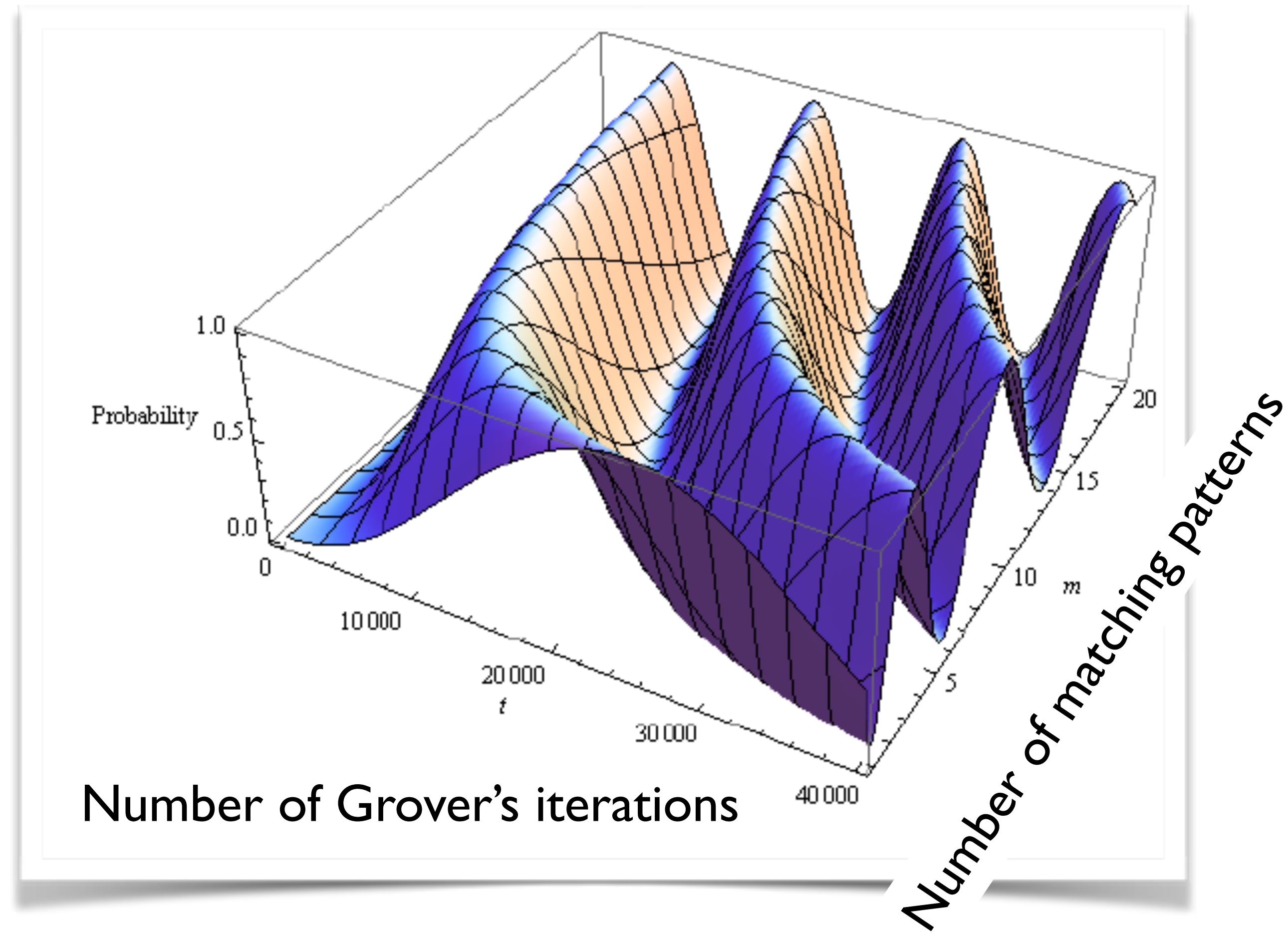
Detector hit identifier (bits)	8	16	32
Binary track pattern (bits)	64	128	256
QuAM register (qubits)	130	258	514
QuAM capacity (patterns)	$\sim 10^{19}$	$\sim 10^{38}$	$\sim 10^{77}$

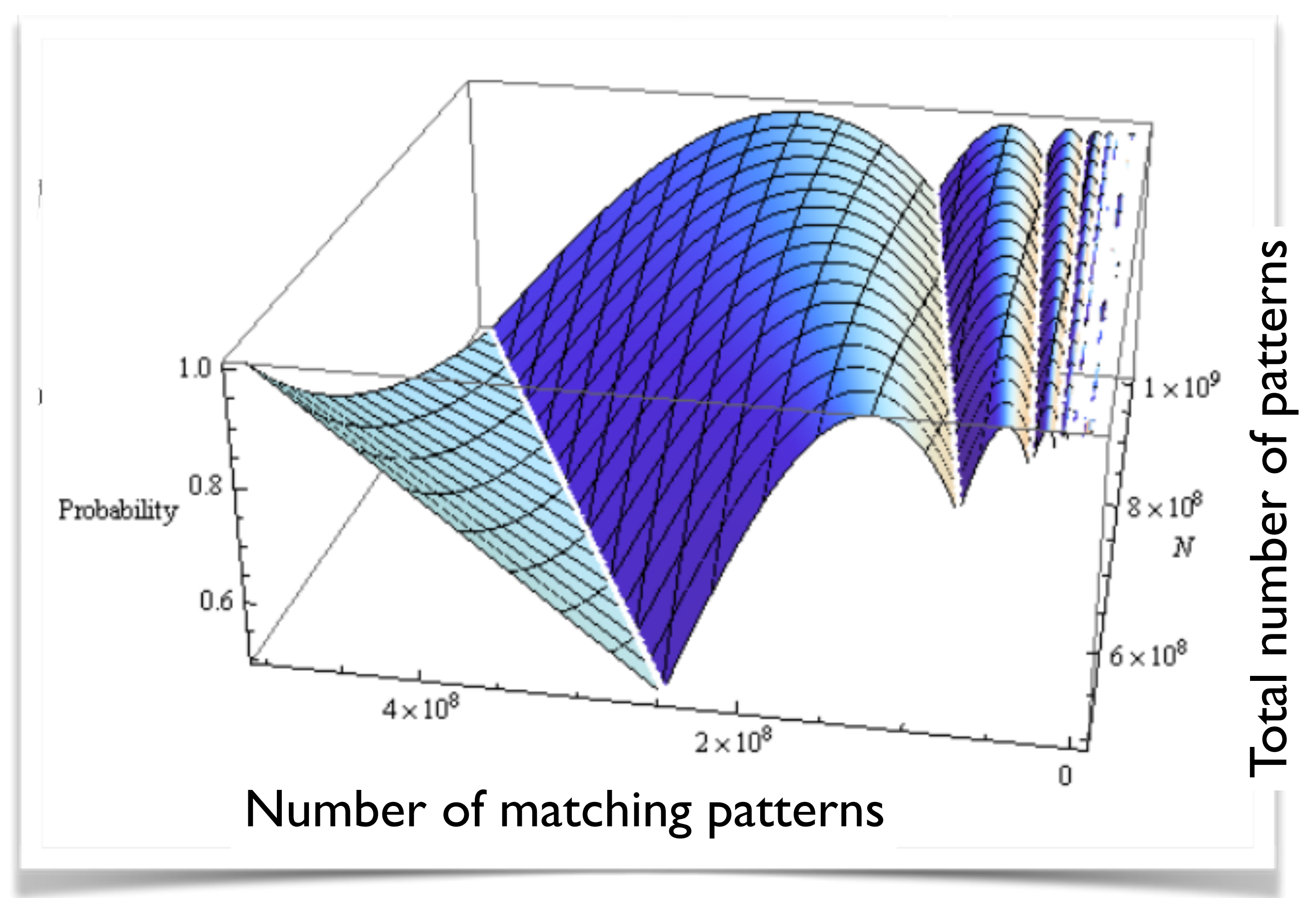
cf: 10^{78}-10^{82} atoms in the known universe



Recall Efficiency

- Theoretical probability of measuring a solution as a function of the number of Grover's iterations and matching patterns (for N = 10^9)
- Peak probability for measuring a solution as a function of the number of matching and total number of patterns stored in QuAM
- Both estimates assume the special case of uniform initial superposition and errorless quantum dynamics

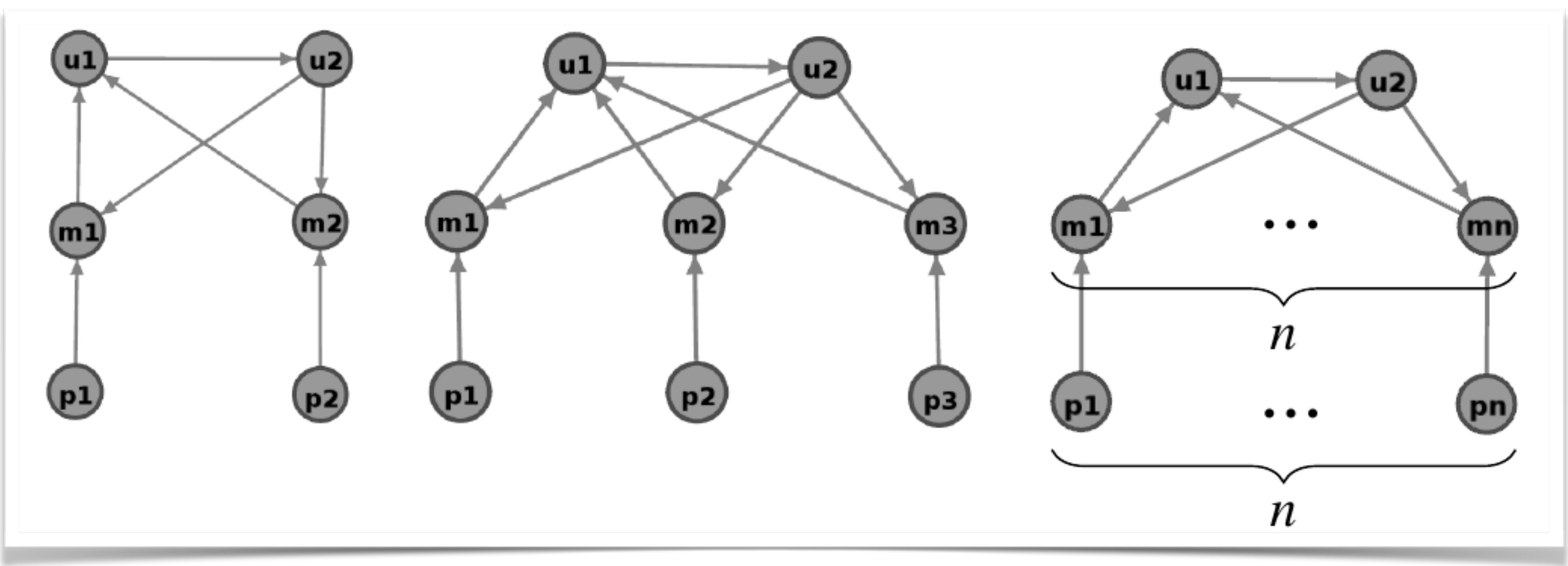




Topological Constraints

- Integral (storage and recall) topological requirements for patterns containing different numbers of bits
  - u: control register
  - p: temporary storage register
  - m: "permanent" storage register

2-bit 3-bit n-bit



Implementation (I)

arXiv:1902.00498

- We developed QuAM circuit generators implementing the Trugenberger's initialization and generalized Grover's algorithms
  - Use open-source quantum computing platform, Qiskit
- Supported backends
  - IBM QE cloud-based quantum chips [5Q Yorktown/Tenerife, 14Q Melbourne, 20Q Tokyo]
  - Local/remote noisy simulators
- Currently working on porting QuAM to 20Q Tokyo

Storage QuAM

```
OPENQASM 2.0;
include "qelib1.inc";
qreg qr[6];
creg cr[6];
x qr[3];
cx qr[3],qr[0];
ccx qr[0],qr[3],qr[4];
ccx qr[1],qr[3],qr[5];
cx qr[1],qr[5];
cx qr[0],qr[4];
x qr[5];
x qr[4];
ccx qr[5],qr[4],qr[2];
cu3(1.23095941734077,3.14159265358979,3.14159265358979) qr[2],qr[3]
ccx qr[5],qr[4],qr[2];
x qr[5];
x qr[4];
cx qr[1],qr[5];
cx qr[0],qr[4];
ccx qr[0],qr[3],qr[4];
ccx qr[1],qr[3],qr[5];
reset qr[0];
reset qr[1];
cx qr[3],qr[0];
```

Snippet

Retrieval QuAM

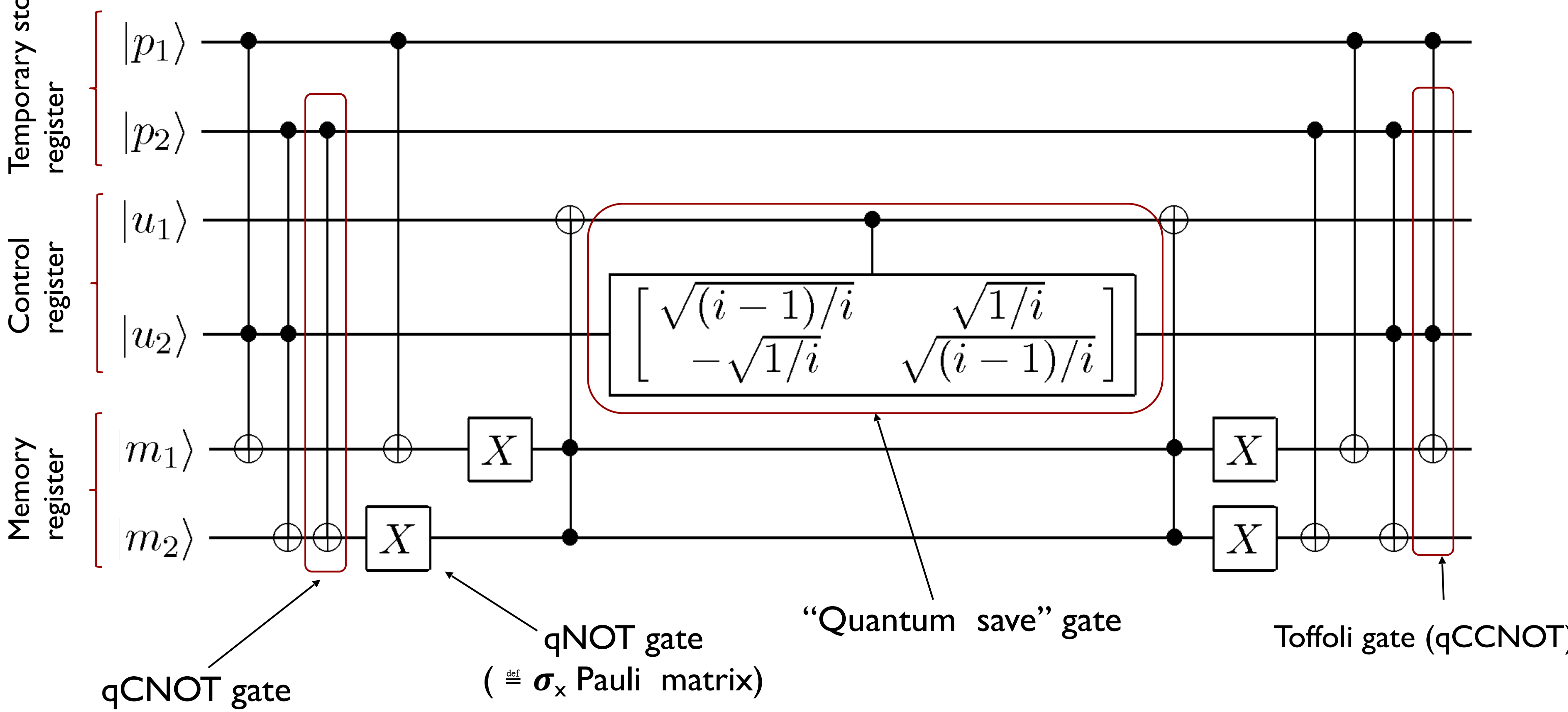
```
s qr[5];
h qr[5];
cx qr[4],qr[5];
h qr[5];
s qr[5];
h qr[4];
h qr[5];
x qr[4];
x qr[5];
h qr[5];
cx qr[4],qr[5];
h qr[5];
x qr[4];
x qr[5];
h qr[4];
h qr[5];
h qr[5];
cx qr[4],qr[5];
h qr[5];
```

Snippet

C.A Trugenberger, Probabilistic Quantum Memories. PRL 87, 6 (2001)

Storage Protocol: Quantum Circuit

Circuit to store a 2-bit pattern



$$1. |\psi_0^1\rangle = |p_1^1, ..., p_d^1; 01; 0_1, ..., 0_d\rangle$$

$$2. |\psi_1^i\rangle = \prod_{j=1}^{d} {}^{2c}\hat{X}_{p_j^i u_2 m_j} |\psi_0^i\rangle$$

$$3. |\psi_2^i\rangle = \prod_{j=1}^{d} \hat{X}_{m_j} {}^{1c}\hat{X}_{p_j^i m_j} |\psi_1^i\rangle$$

$$4. |\psi_3^i\rangle = {}^{dc}\hat{X}_{m_1 \ldots m_d u_1} |\psi_2^i\rangle$$

$$5. |\psi_4^i\rangle = {}^{1c}\hat{S}_{u_1 u_2}(p+1-i) |\psi_3^i\rangle$$

$$6. |\psi_5^i\rangle = {}^{dc}\hat{X}_{m_1 \ldots m_d u_1} |\psi_4^i\rangle$$

$$7. |\psi_6^i\rangle = \prod_{j=d}^{1} {}^{1c}\hat{X}_{p_j^i m_j} \hat{X}_{m_j} |\psi_1^i\rangle$$

$$= \frac{1}{\sqrt{p}} \sum_{k=1}^{i} |p^i; 00; p^k\rangle + \sqrt{\frac{p-i}{p}} |p^i; 01; p^i\rangle$$

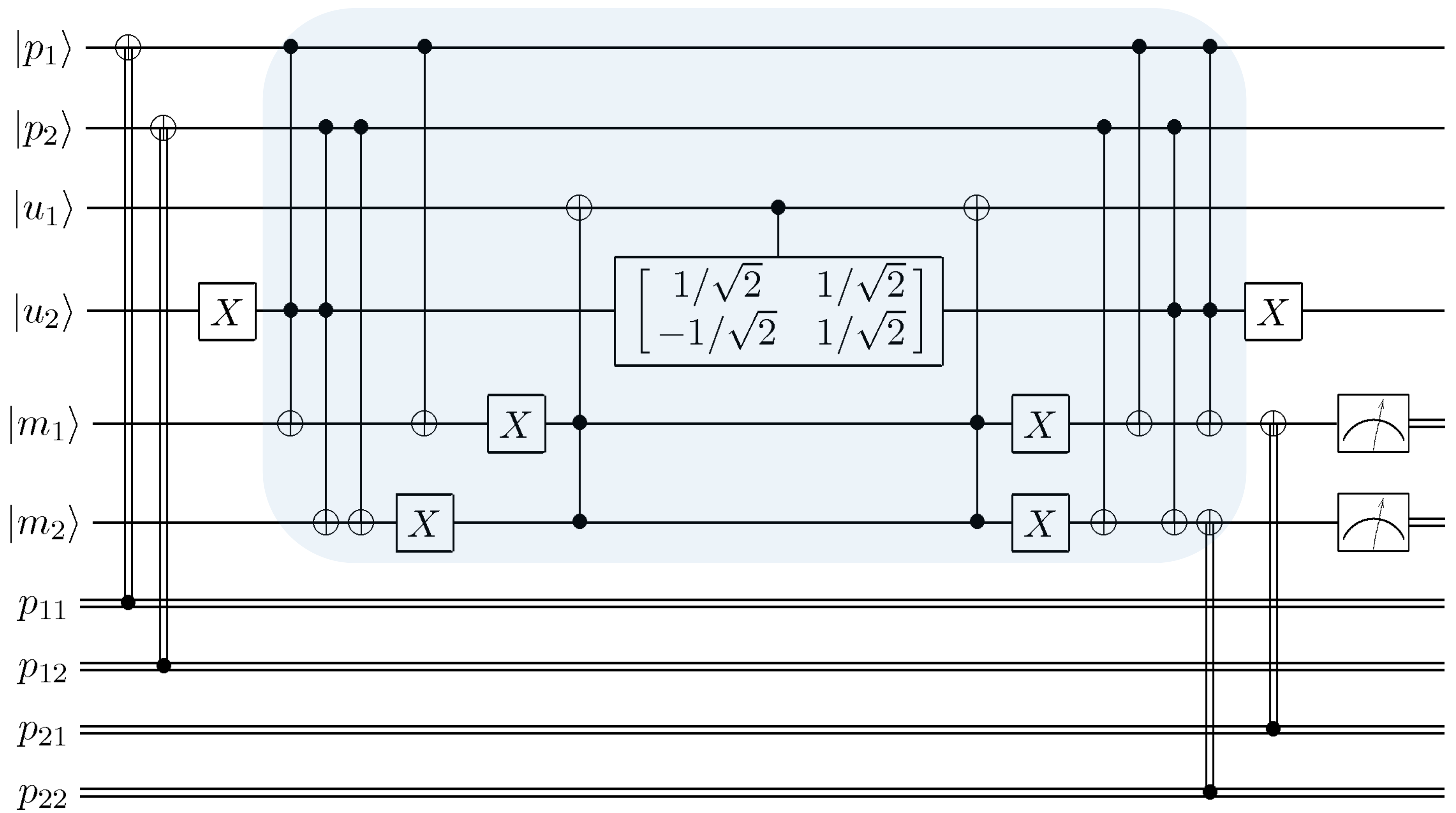
$$8. |\psi_7^i\rangle = \prod_{j=d}^{1} {}^{2c}\hat{X}_{p_j^i u_2 m_j} |\psi_6^i\rangle$$

C.A Trugenberger, Probabilistic Quantum Memories. PRL87, 6 (2001)

Storage protocol: Example of 2-bit pattern

End-to-end circuit for storing two 2-bit patterns: "01" and "10"

$$|00;00;00\rangle$$



Classical bits for pattern read-in

Patterns '01' and '10' saved

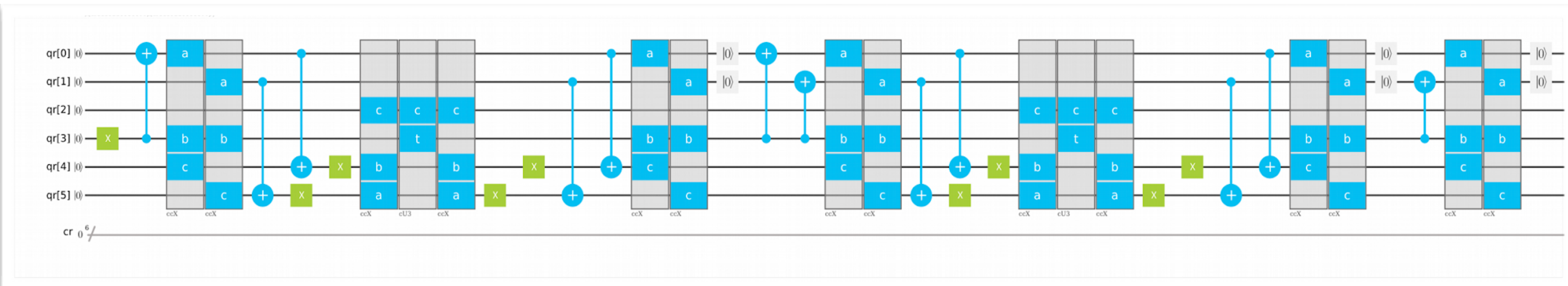
$$\frac{1}{\sqrt{2}}|01;00\rangle\left(|01\rangle + |10\rangle\right)$$

Implementation (2)

arXiv:1902.00498

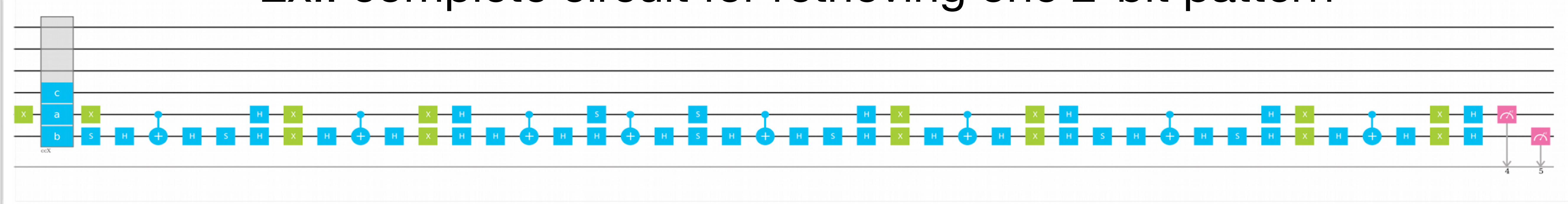
QuAM storage circuit generator

Ex.: complete circuit for retrieving one 2-bit pattern



QuAM retrieval circuit generator

Ex.: complete circuit for retrieving one 2-bit pattern



Track Reconstruction
2. Quantum Annealing

arXiv:1902.08324

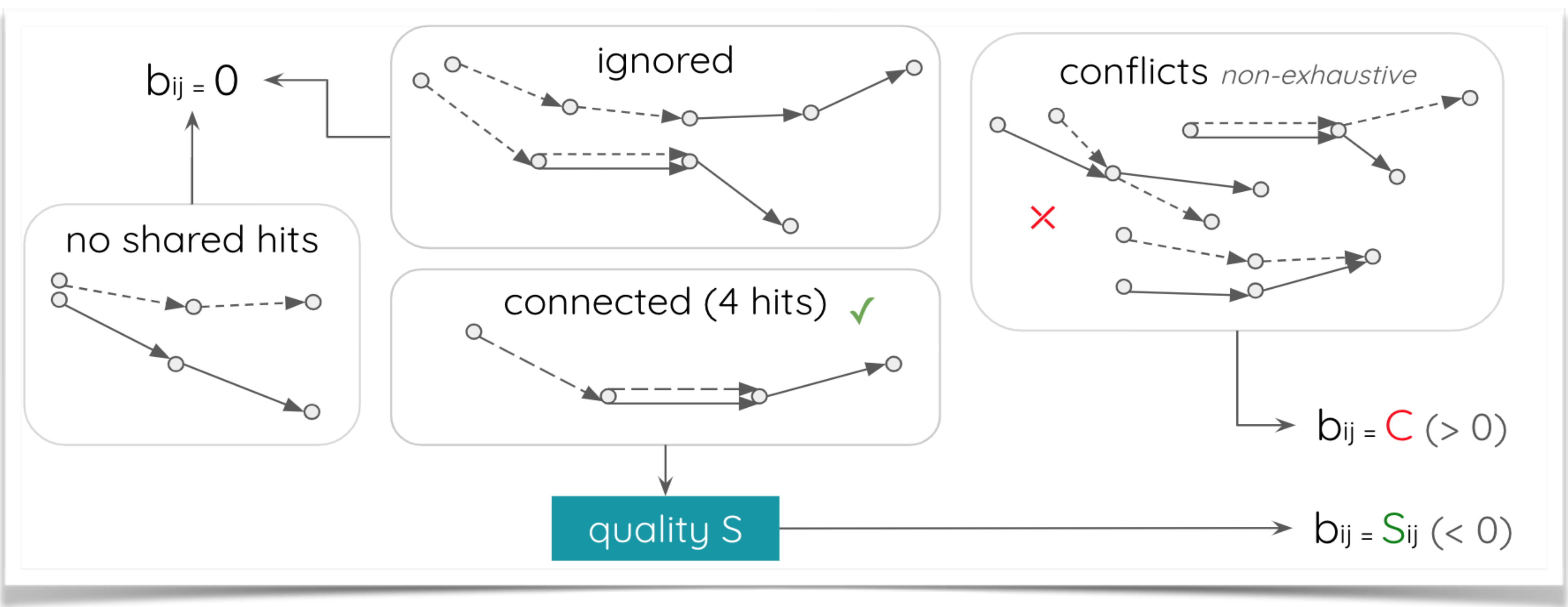
https://github.com/derlin/hepqpr-qallse

Also, see talk by J.R.Vlimant for a similar study

Quantum Annealing

arXiv:1902.08324

- Explore how Quantum Annealing could bring speed improvements to pattern recognition
  - Implement QUBO minimisation on D-Wave and study scaling with track multiplicity
- Inspired from [1], but use triplets instead of doublets as binary variables
- Encode the quality of the triplets based on physics properties. The pair-wise connections b act as constraints (>0) or incentives (<0):



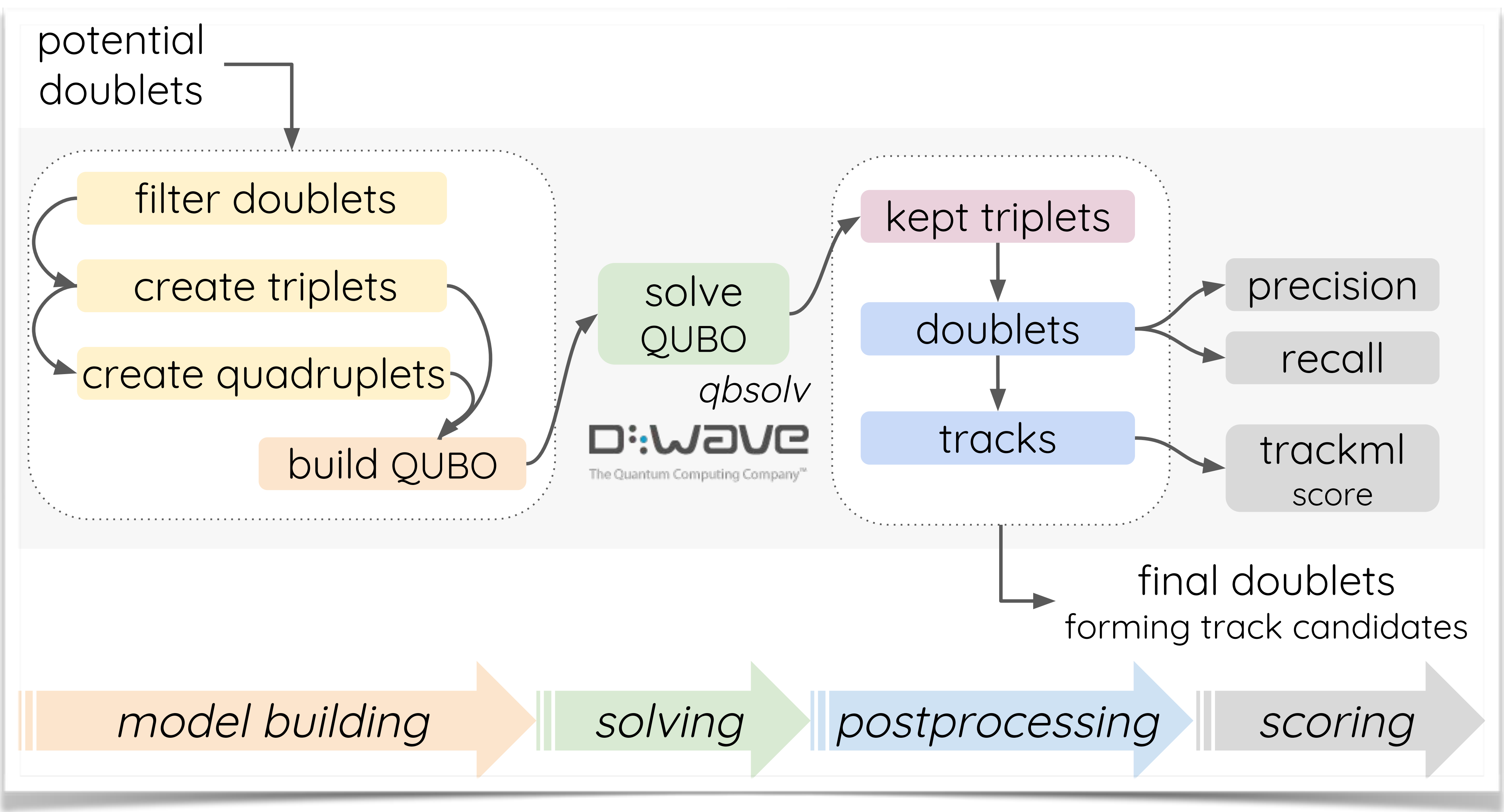
- Minimizing O means selecting the best triplets to form track candidates.

[1] Stimpfl-Abele, G., & Garrido, L. (1991). Fast track finding with neural networks. *Computer Physics Communications*, *64*(1), 46-56.

Implementation

arXiv:1902.08324

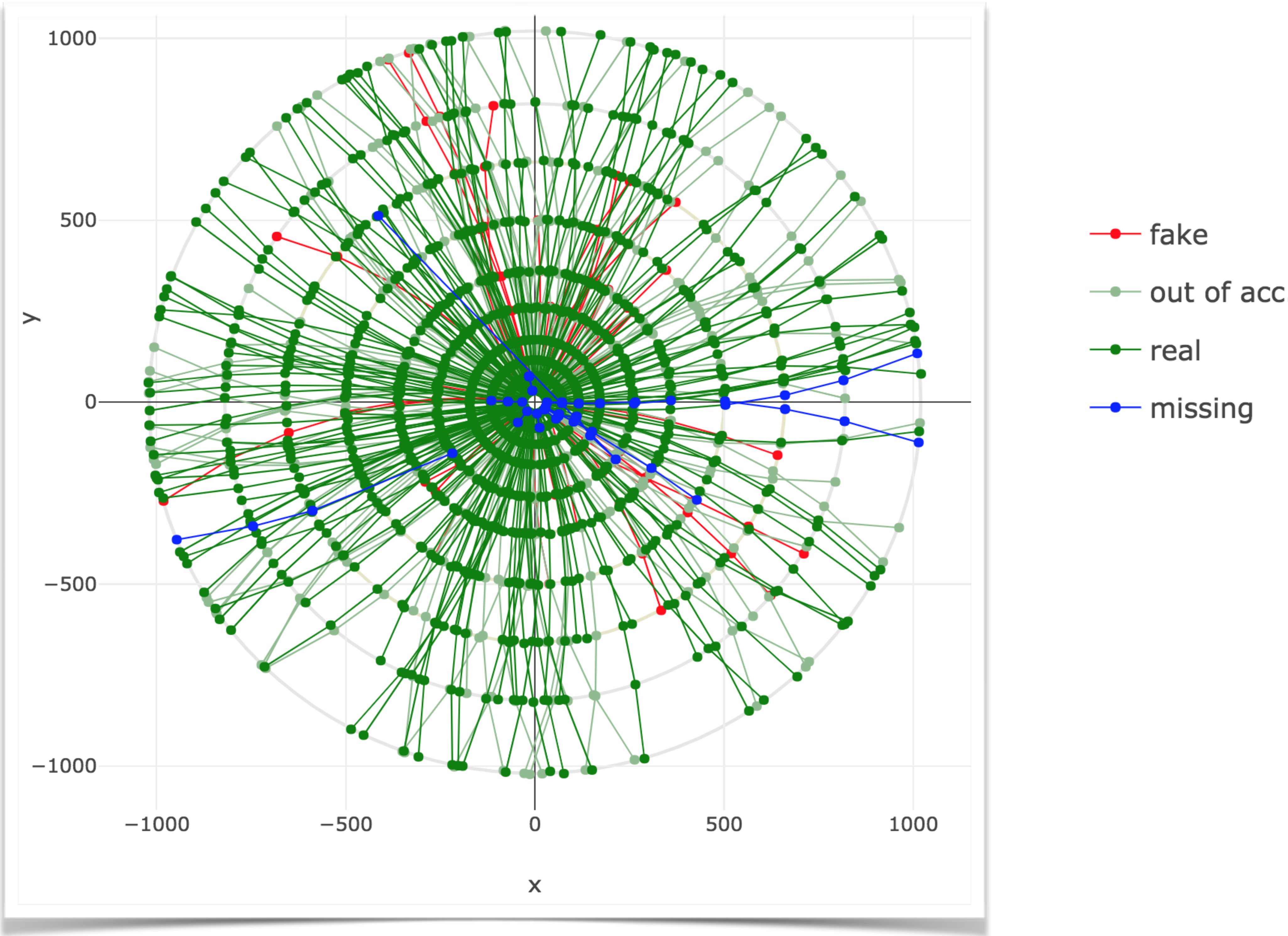
- Dataset: simplified TrackML dataset, focus on barrel, 1+ GeV, at least 5 hits
  - Toy dataset, but representative of expected conditions at the HL-LHC
- QUBO solvers: qbsolv (D-Wave + simulation), neal (classical)
- D-Wave 2X (1152 qubits), D-Wave 2000Q (2048 qubits)



Performance

arXiv:1902.08324

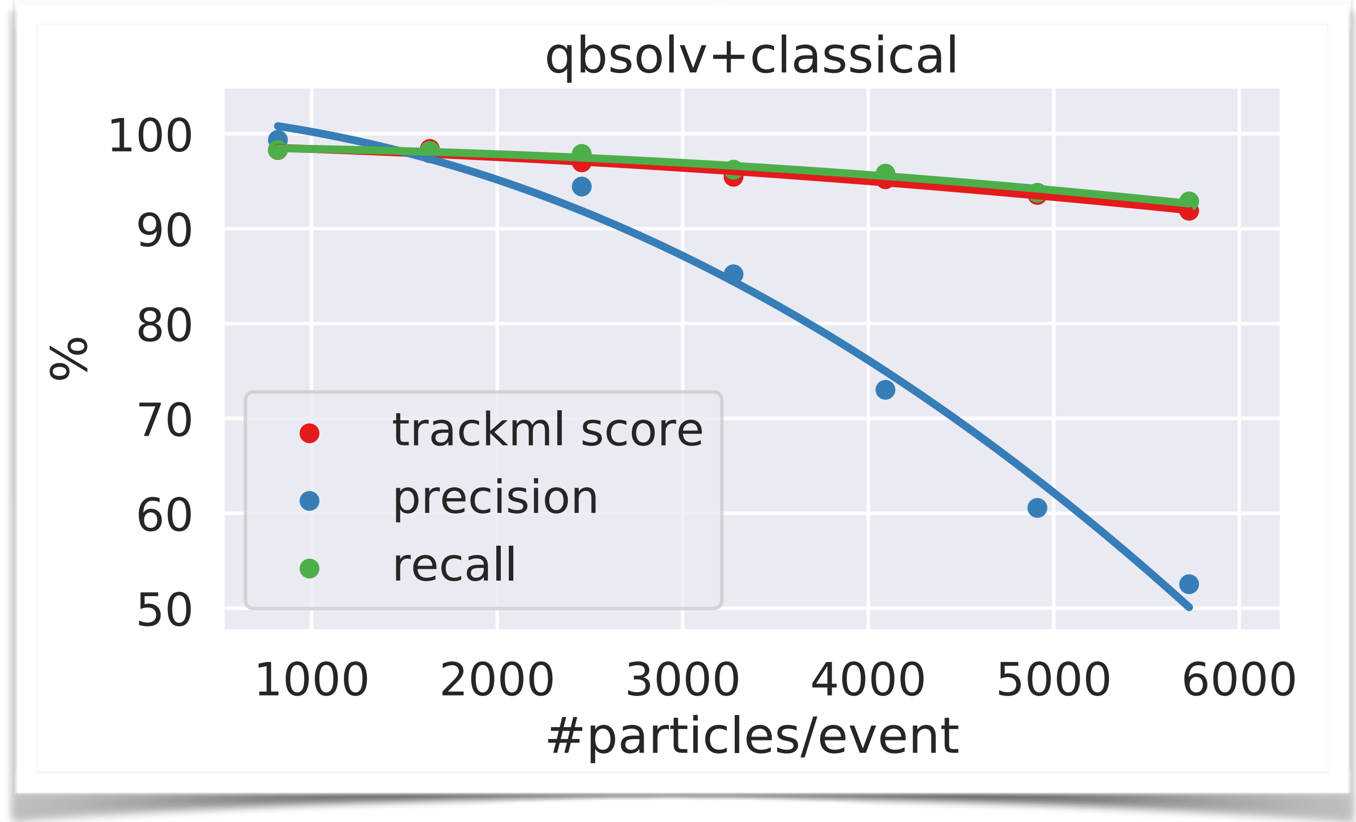
Doublets for a dataset of 2456 particles and 16855 hits

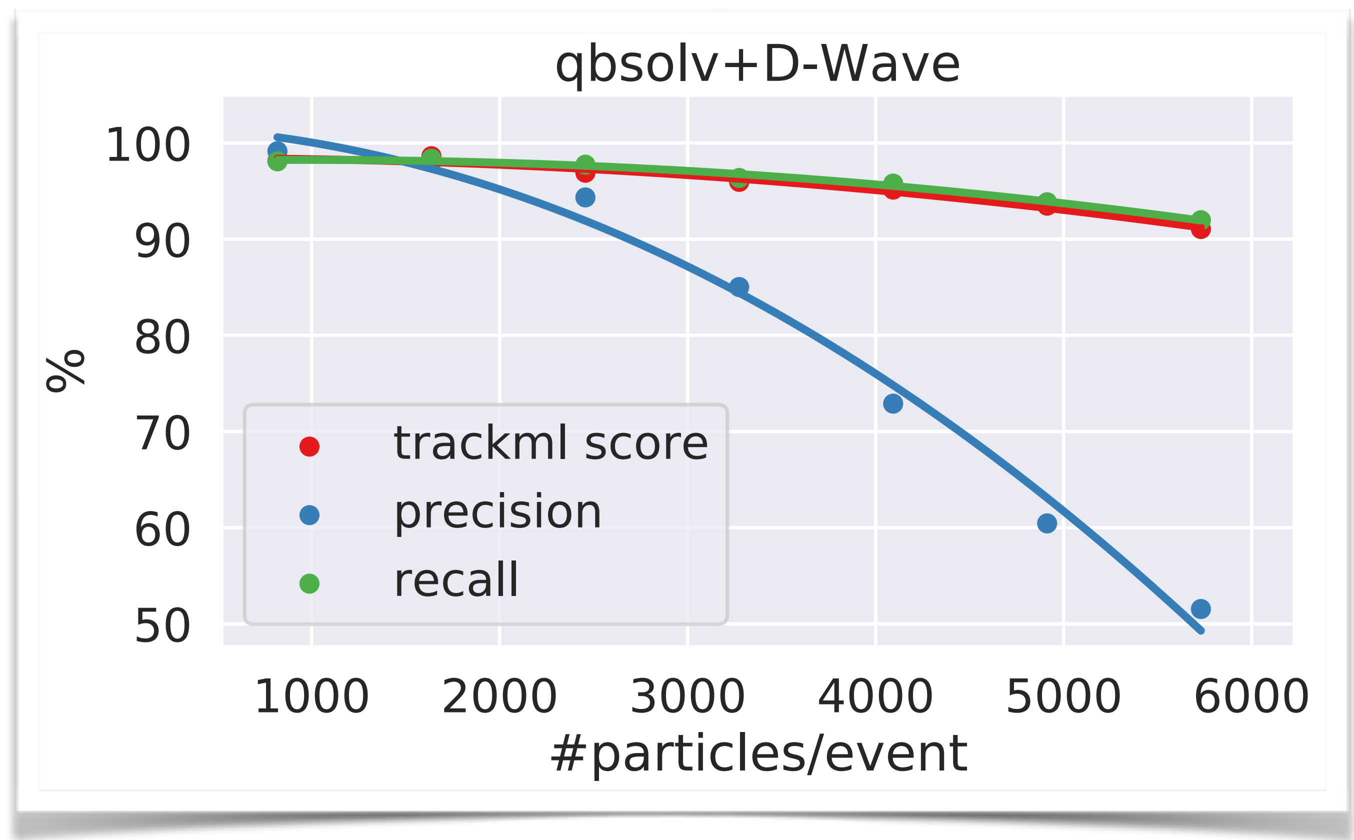


Performance (2)

arXiv:1902.08324

Physics performance as a function of occupancy using a D-Wave 2X (qbsolv).



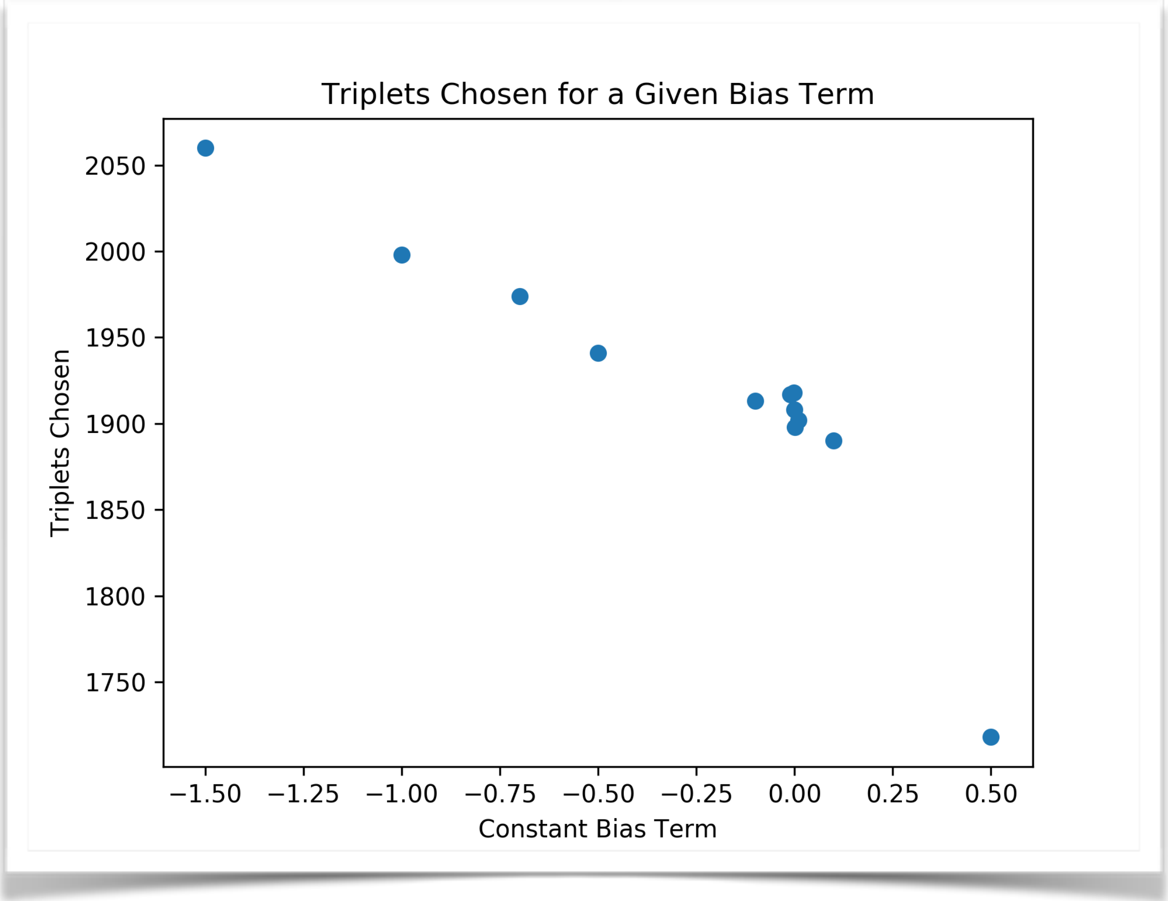


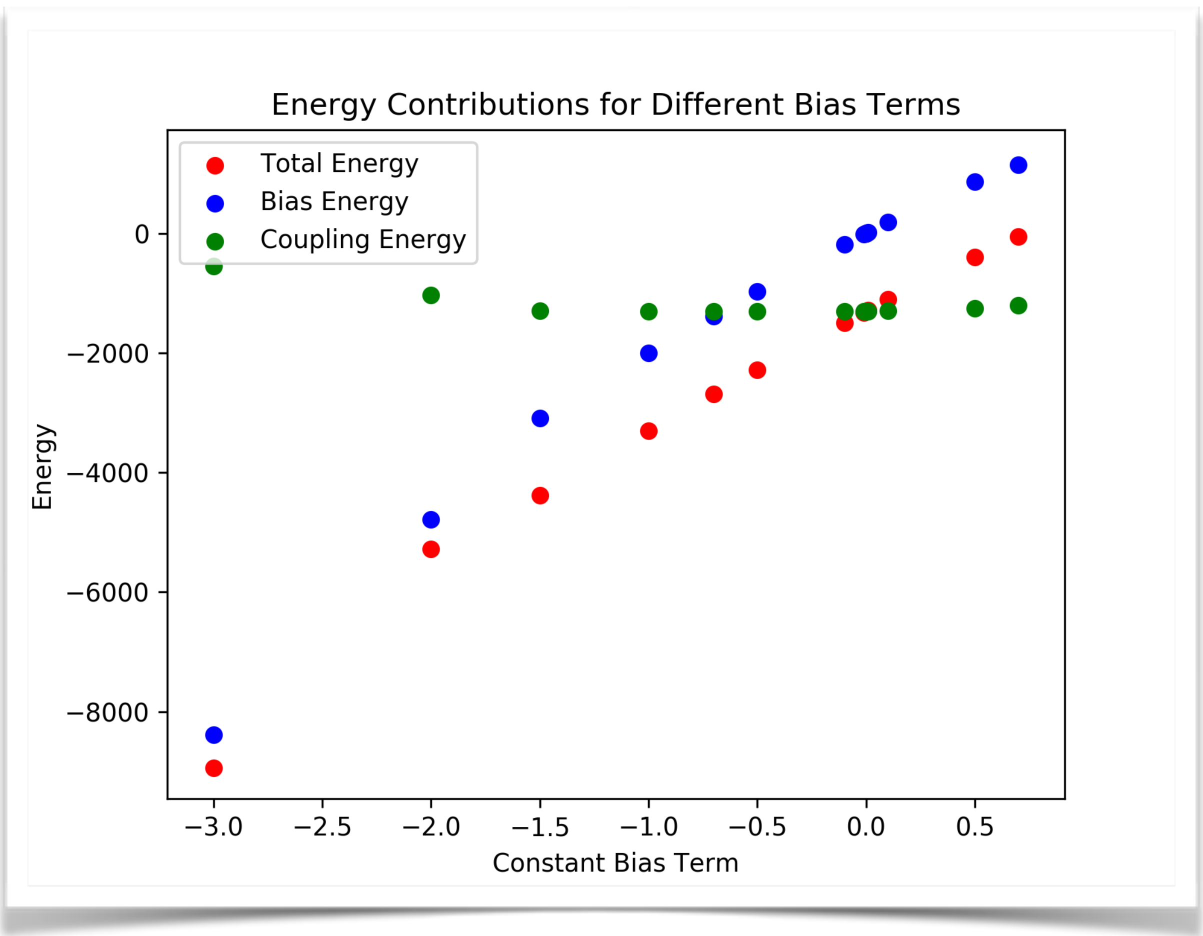
Timing building: 0-20 min | solving: 0-12s (sim), 0-56 min (D-Wave)

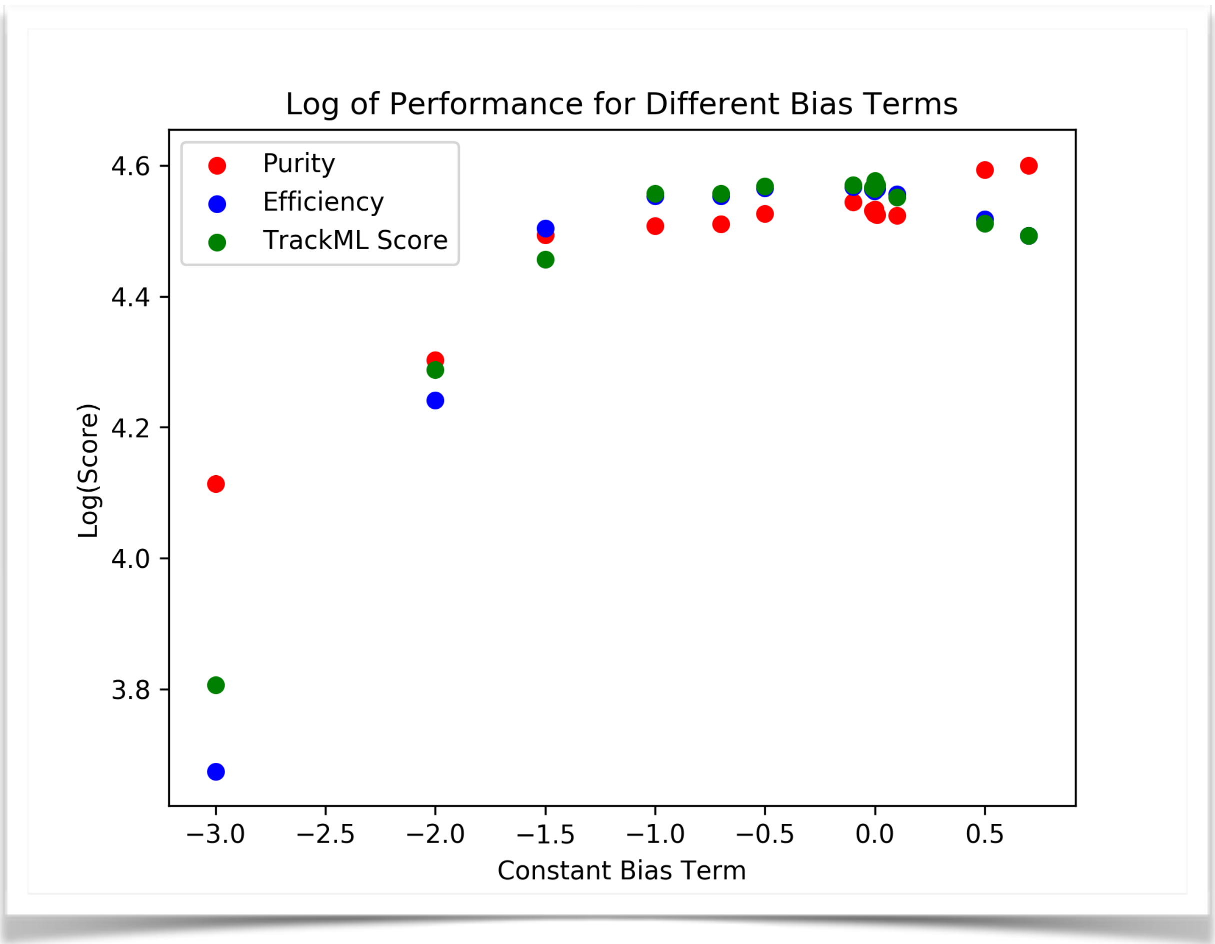
D-Wave | sim. Same physics, important time overhead with D-Wave

Exploring the bias term

- Study performance of the qubo when varying the bias term on sample with 30% of expected HL-LHC lumi
- Performance is very sensitive to the value of the bias
- Generally do not see improved performance by including a non-zero bias term



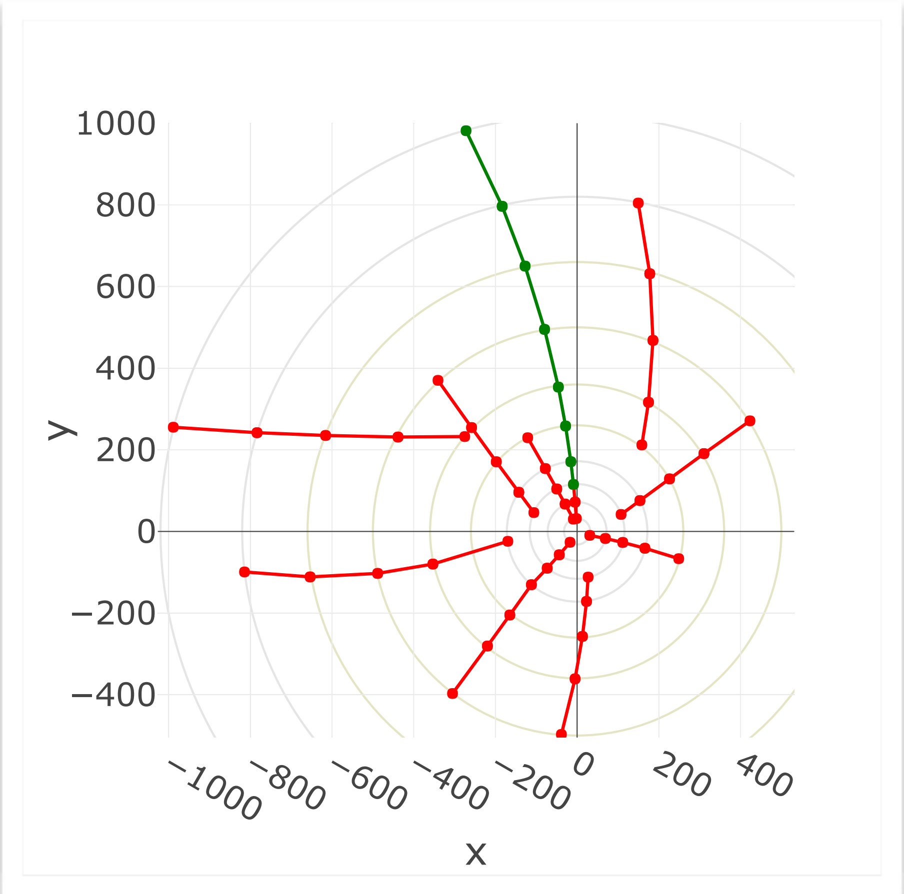


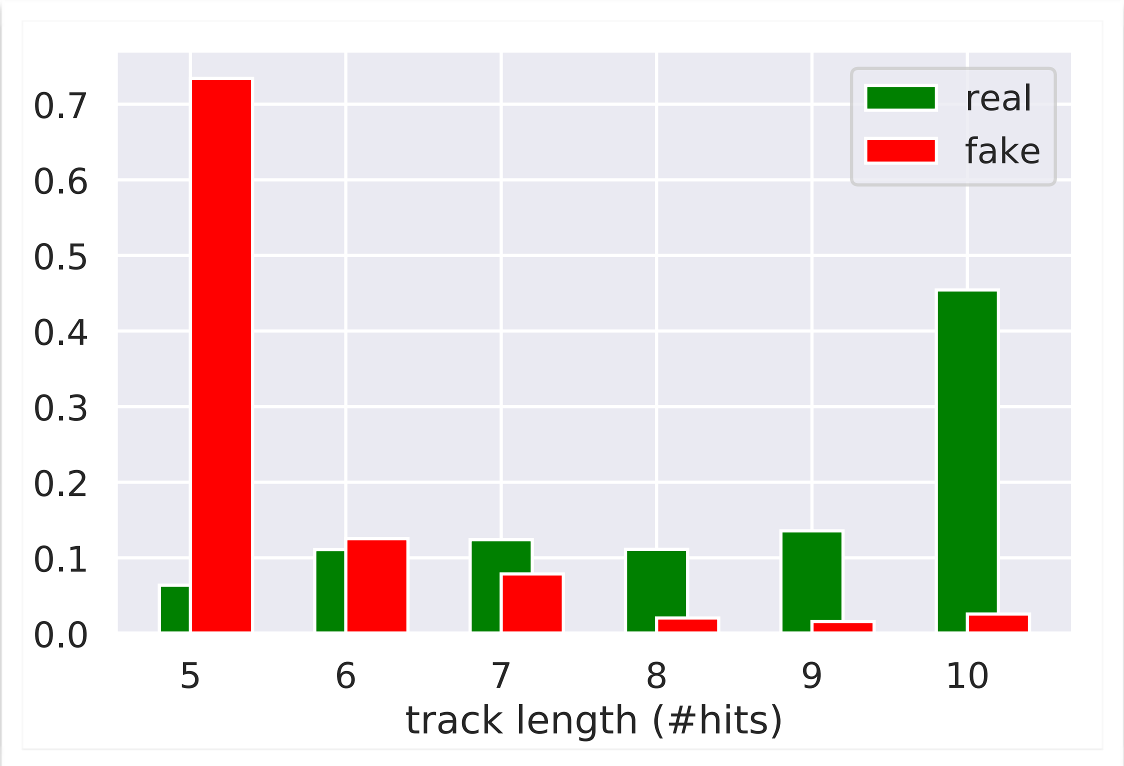


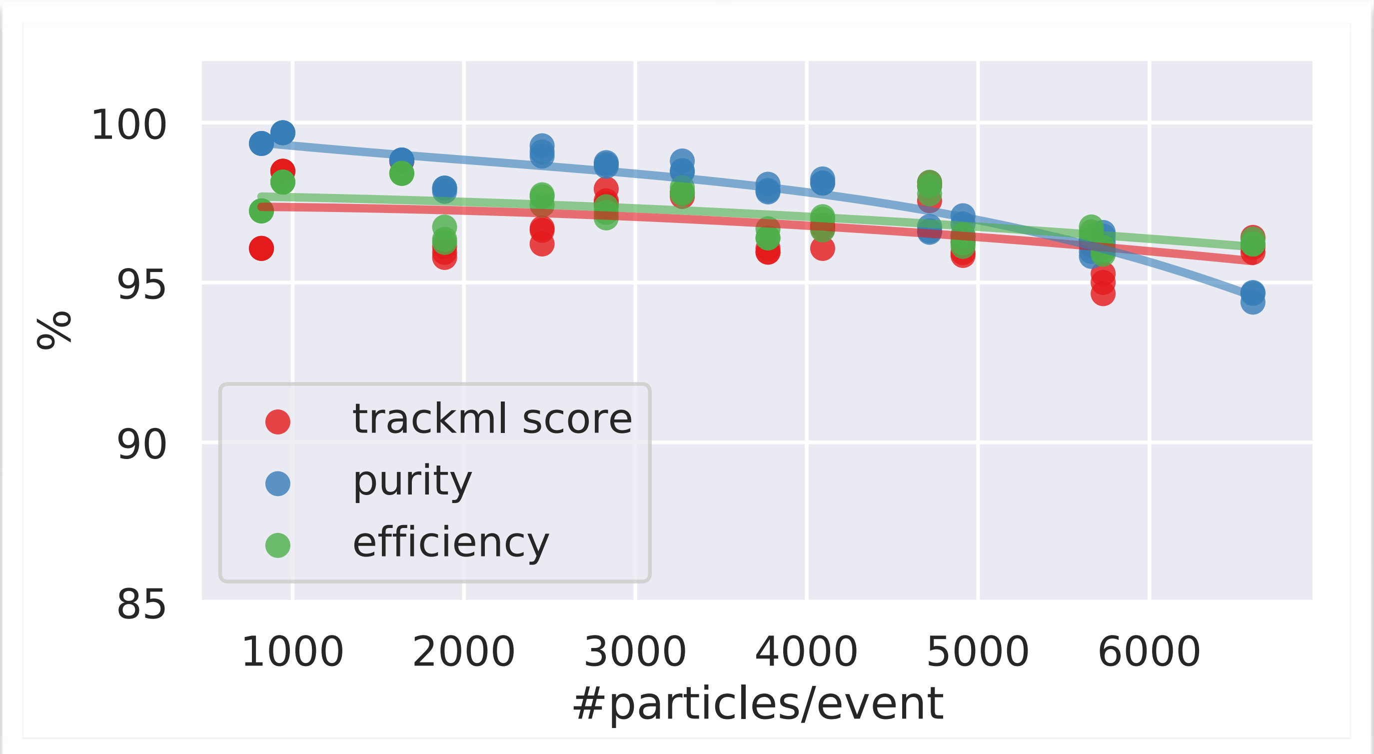
Reducing Fakes

arXiv:1902.08324

- At multiplicities approaching the HL-LHC, we find a significant contribution of fakes
- Exploring methods to reduce fakes
  - tighten quality requirements
  - refining conflict & bias terms, e.g. including vertex assumptions







Conclusion

- Charged particle tracking is well-recognised as being a key computing challenge for the HL-LHC
- Many different approaches are currently being pursued to exploit new hardware and software paradigms
- Presented here a brief summary of the HEP.QPR project, which is exploring the use of quantum computers for pattern recognition
  - Quantum associative memory could provide exponential storage capacity with optimal time access
  - Quantum annealing could provide algorithms with execution time independent of the particle multiplicity
- Its definitely very early days for quantum computers, but, by exploring the currently available machines, we can begin to determine algorithms and also provide input on their design towards our needs

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